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ENERGY EFFICIENT ENGINE
HIGH-PRESSURE TURBINE
LEAKAGE TECHNOLOGY REPORT



Prepared
by

W. B. Gardner, Program Manager
Energy Efficient Engine Component
Development and Integration Program

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft
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Feather Seals	Seal										
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FOREWORD

The Energy Efficient Engine Component Development and Integration Program is being conducted under parallel National Aeronautics and Space Administration contracts to Pratt & Whitney Aircraft Group and General Electric Company. The overall project is under the direction of Mr. Carl C. Ciepluch. Mr. John W. Schaefer is the NASA Assistant Project Manager for the Pratt & Whitney Aircraft effort under NASA Contract NAS3-20646, and Mr. Michael Vanco is the NASA Project Engineer responsible for the portion of the project described in this report. Mr. William B. Gardner is manager of the Energy Efficient Engine Project at Pratt & Whitney Aircraft Group.

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LIST OF SYMBOLS

EDM	Electro-Discharge Machined
EEE	Energy Efficient Engine
F	Farenheit
FEDD	For Early Domestic Dissemination
I.D.	Inner Diameter
OAS	Outer Air Seal
O.D.	Outer Diameter

1.0 SUMMARY

The leakage test program was one of several supporting technology programs structured to provide guidance to the Energy Efficient Engine High-Pressure Turbine Component Design Effort. It accomplished its task by identifying and evaluating techniques for leakage reduction and by providing the results of these evaluations to the component design effort in a timely manner. Test models were used to simulate component leak paths and to evaluate leakage reduction concepts. These models simulated the blade/disk attachment, the vane inner platform attachment, and the vane outer platform attachment combined with the blade outer airseal.

Disk-blade attachment testing indicated that leakage in this area could be reduced to very low levels by paying careful attention to the tolerances along the contact surface between the blade vibration damper and the blade platform contact surface. The leakage was so low, in fact, that providing enough air to cool hot parts (i.e., disk sideplates) could be the dominant concern in the component design.

The aim of the extensive feather seal testing was to achieve a goal for an effective leakage gap of one mil (.001 inch) per inch of feather seal length. Results indicated that effective gaps even below the goal level were achievable by (1) maintaining close tolerances between feather seals and their slots to minimize end gaps and limit seal rotation. (2) avoiding feather seal overlap, and (3) minimizing feather seal intersections.

"W" seals were shown to be effective leakage control devices, even though it proved somewhat difficult to measure accurately the leakage flow past them in the test rig. Wire rope, in its present state of development, was shown not to be an effective sealing concept for application to the component design.

2.0 INTRODUCTION

The objective of the NASA E³ Development and Integration program is to develop, evaluate, and demonstrate the technology for achieving lower installed fuel consumption and lower operating costs in future commercial turbofan engines. NASA has set minimum goals of 12 percent reduction in thrust specific fuel consumption, 5 percent reduction in direct operating cost, and 50 percent reduction in performance degradation for the EEE engine relative to the JT9D-7A reference engine. In addition, environmental goals for emissions (to meet the proposed EPA 1981 regulations) and noise (to meet the FAR 36-1978 standards) have been established.

In a high performance gas turbine engine, gaspath leakage can be detrimental to the achievement of performance goals because of its disruptive influence on the aerodynamics of the components affected. This is particularly true for the single stage high pressure turbine design concept utilized in the Energy Efficient Engine Flight Propulsion System. Consequently, an aggressive leakage goal has been established for the high pressure turbine. This goal is nominally one-half the leakage experienced in the high pressure turbines of current high bypass ratio turbofan engines.

The purpose of the High-Pressure Turbine Leakage Supporting Technology Program was, therefore, to (1) investigate the potential sources of leakage in the Energy Efficient Engine High Pressure Turbine Design and (2) define the approach to reducing leakage from these sources within the constraints of the component design and sealing concepts evaluated.

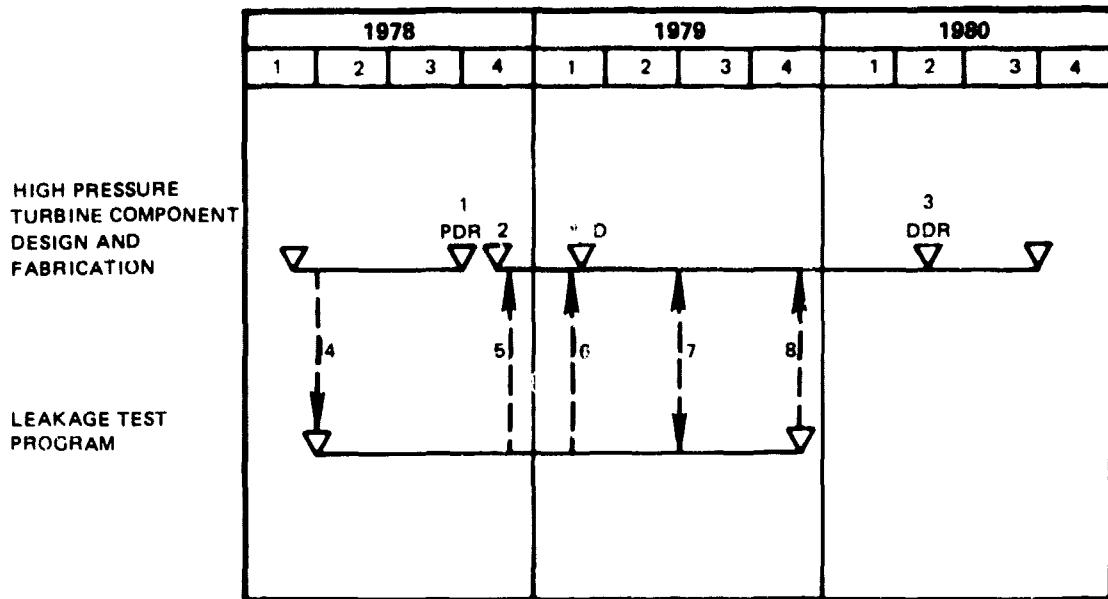
Metal test rigs to simulate leak paths and evaluate sealing concepts were designed and fabricated for blade disk attachment, vane attachment, and vane attachment with blade outer airseal. For the disk-blade attachment area, a plastic visualization model was also constructed to establish assembly and sealing requirements as a guide to the component detailed design efforts.

Following initial model testing, areas of high leakage were reevaluated, improved design concepts incorporated, and retesting conducted to verify that additional leakage reduction was subsequently achieved.

This supporting technology program was conducted to permit timely interaction with the high-pressure turbine component effort, thereby ensuring that the evaluated leakage control concepts could be easily tailored to the requirements of the high-pressure turbine component (see Figure 1).

This report covers the definition of the potential leakage paths, analysis and design of the test rigs that could simulate these leakage paths, and the test results obtained.

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- *D - CRITICAL DECISION POINT FOR SELECTION OF VANE & BLADE AERODYNAMICS.
- 1 - COMPONENT PRELIMINARY DESIGN COMPLETED.
 - 2 - COMPONENT DETAILED DESIGN INITIATED.
 - 3 - COMPONENT DETAILED DESIGN COMPLETED.
 - 4 - POTENTIAL COMPONENT LEAK PATHS DEFINED. INFORMATION SUPPLIED TO LEAKAGE PROGRAM TO INITIATE RIG ANALYSIS AND DESIGN EFFORTS.
 - 5 - DISK-BLADE ATTACHMENT RESULTS TO COMPONENT DESIGN.
 - 6 - PLASTIC MODEL OF DISK-BLADE ATTACHMENT TO COMPONENT DESIGN.
 - 7 - VANE OUTER ATTACHMENT FEATHER SEAL CONFIGURATION MODIFIED.
 - 8 - FINAL VANE PLATFORM AND OUTER AIRSEAL RESULTS TO COMPONENT DESIGN.

Figure 1 High-Pressure Turbine Leakage Program Logic Diagram - The overall timing of this supporting technology program permitted timely interaction with the high-pressure turbine component effort.

3.0 ANALYSIS AND DESIGN

3.1 Overview

As indicated in Figure 1, potential leakage paths were defined during the High-Pressure Turbine Component Preliminary Analysis and Design effort. These paths are indicated in Figure 2 for the four primary leakage sources shown. The objective of the analysis and design effort in the Leakage Program was to provide test rigs that could simulate accurately the actual component leakage paths and could be used to evaluate a wide range of sealing concepts.

Sealing concepts evaluated during the course of the program included "W" seals, wire rope, feather seals, and sheet metal diaphragm seals. Within these broad categories, a number of variations were evaluated in order to evolve the minimum leakage design. Typical of these were the variations in feather seal design illustrated in Figure 3. All of the test rigs incorporated gaps similar to those expected in the turbine component assembly. Although it is recognized that random tolerance variations in these gaps occur in an actual component assembly and could cause significant variations in leakage flow areas, it was impossible to account for these variations in the rig. However, it was felt that not being able to account for these variations had no significant impact on program results.

3.2 Blade Attachment Rig

The blade attachment rig is shown in Figure 4(a). Major components of this rig included simulations of the disk and rotor platform, front and rear sideplates, and damper seals. The three major leak paths that this rig was designed to simulate are shown in Figure 4(b): flow from the disk cavity past the front of the damper seal, flow between disk and front sideplate, and flow between disk and rear sideplate. Flow from these three sources converged in the damper/blade neck cavity and subsequently leaked past the damper seal and the "W" seal located at the interface of the disk and the tip of the rear sideplate. In addition to the rig shown, a plastic model of the component blade-disk attachment area was constructed to provide a visual description of assembly and sealing requirements, as a guide to the component detailed design effort. The sealing concepts chosen for evaluation as well as their locations are identified in Figure 4(b).

3.3 Vane Inner Attachment Rig

The vane inner attachment rig is shown in Figure 5(a); major components of this rig included simulations of the vane inner platform and platform interfaces which are characteristic of the high pressure turbine vane. The major leak paths that this rig was designed to simulate are shown in Figure 5(b): 1) flow from the combustor inner liner cavity past the vane inner diameter front attachment, 2) flow between inner platform segment gaps, and 3) flow past the inner diameter rear attachment flange.

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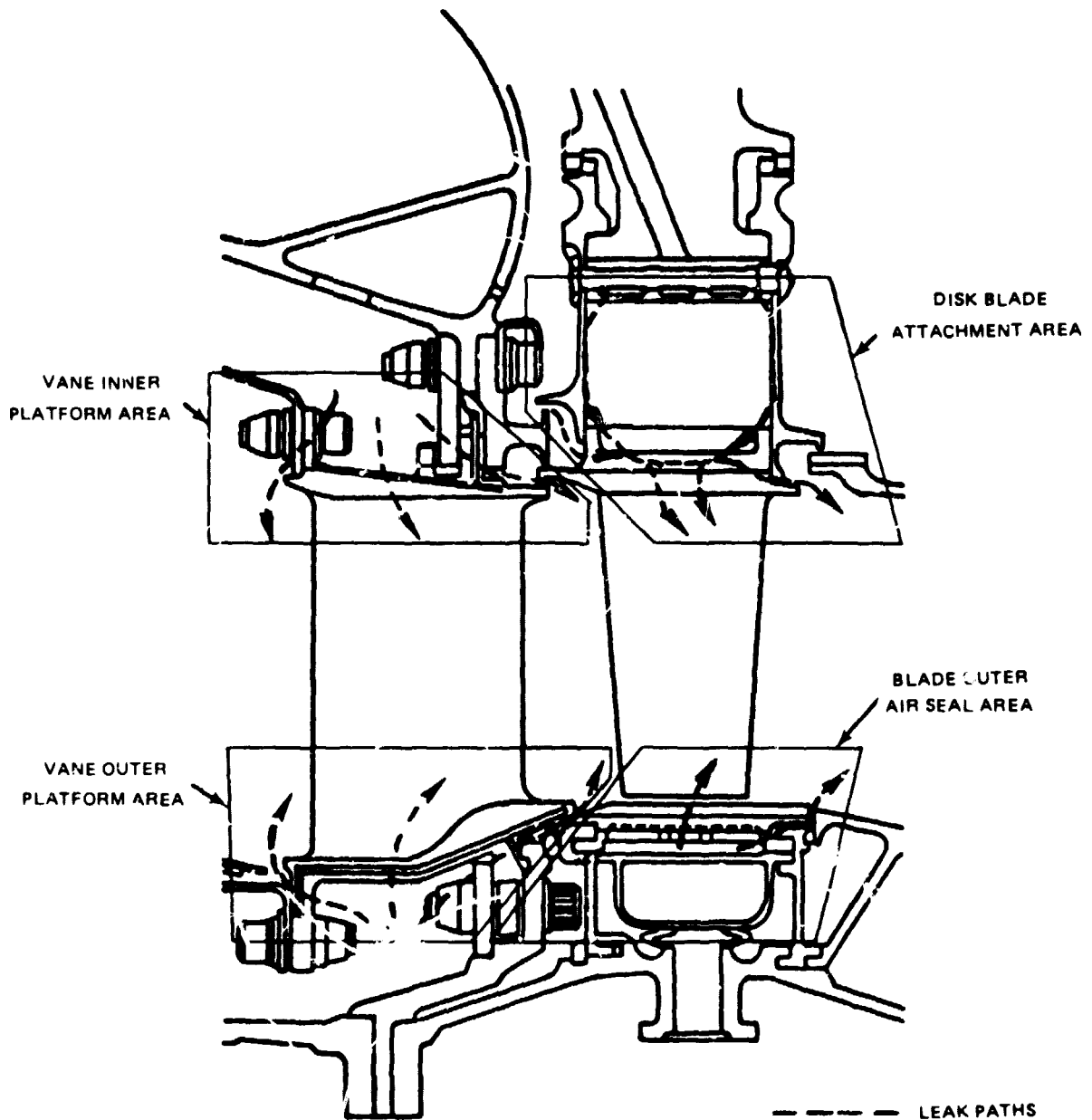
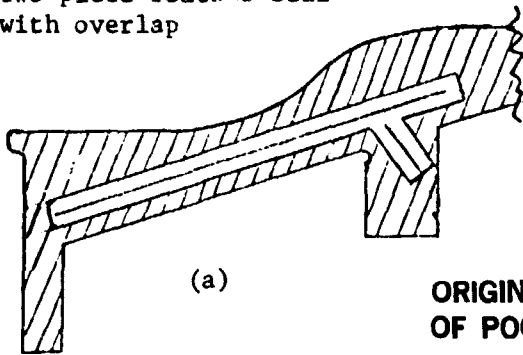
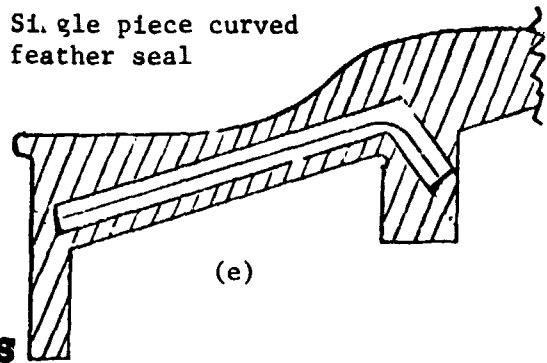


Figure 2 Energy Efficient Engine High-Pressure Turbine Preliminary Design - The leakage paths are indicated for the four primary leakage sources shown.

Two-piece feather seal
with overlap

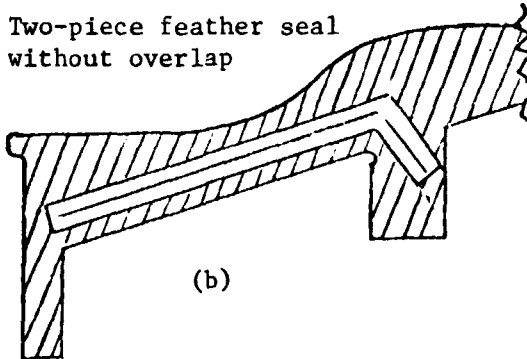


Single piece curved
feather seal

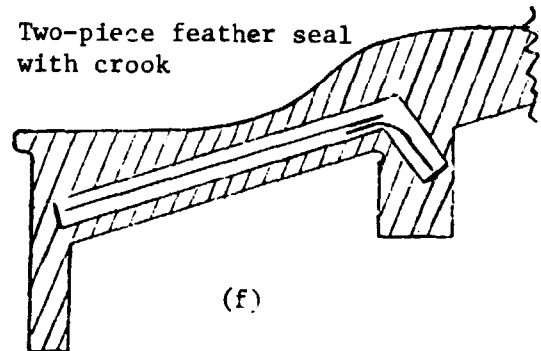


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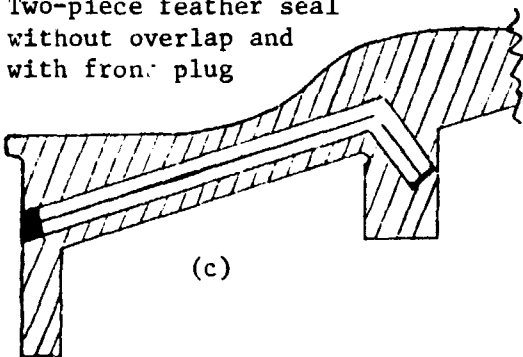
Two-piece feather seal
without overlap



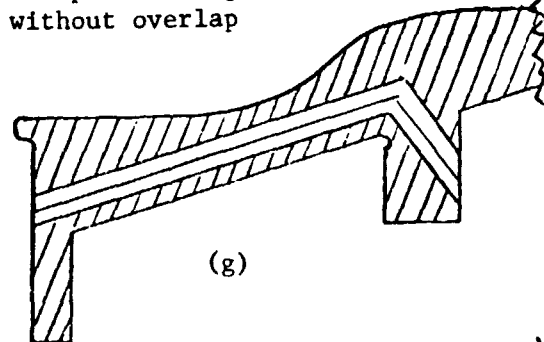
Two-piece feather seal
with crook



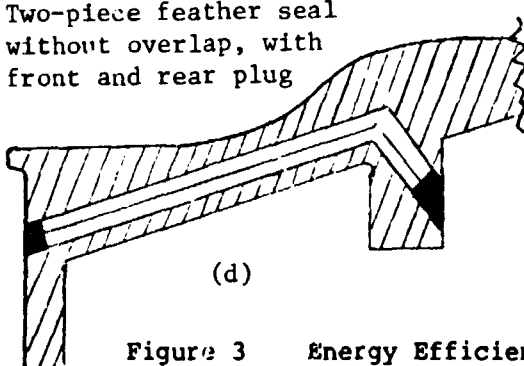
Two-piece feather seal
without overlap and
with front plug



Two-piece "long" feather seal
without overlap



Two-piece feather seal
without overlap, with
front and rear plug



Four-piece feather seal

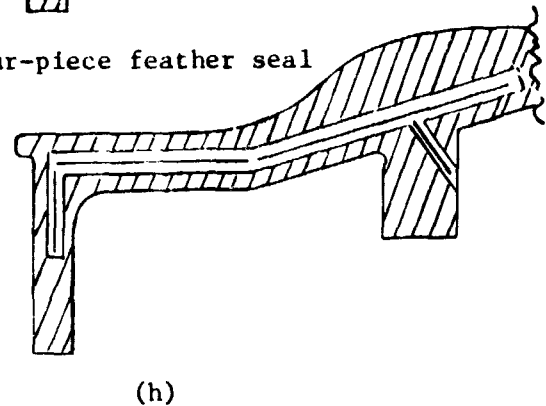


Figure 3

Energy Efficient Engine High-Pressure Turbine Feather
Seals - Various promising feather seal configurations were
evaluated. All of the test rigs incorporated gaps similar
to those expected in the turbine component assembly.

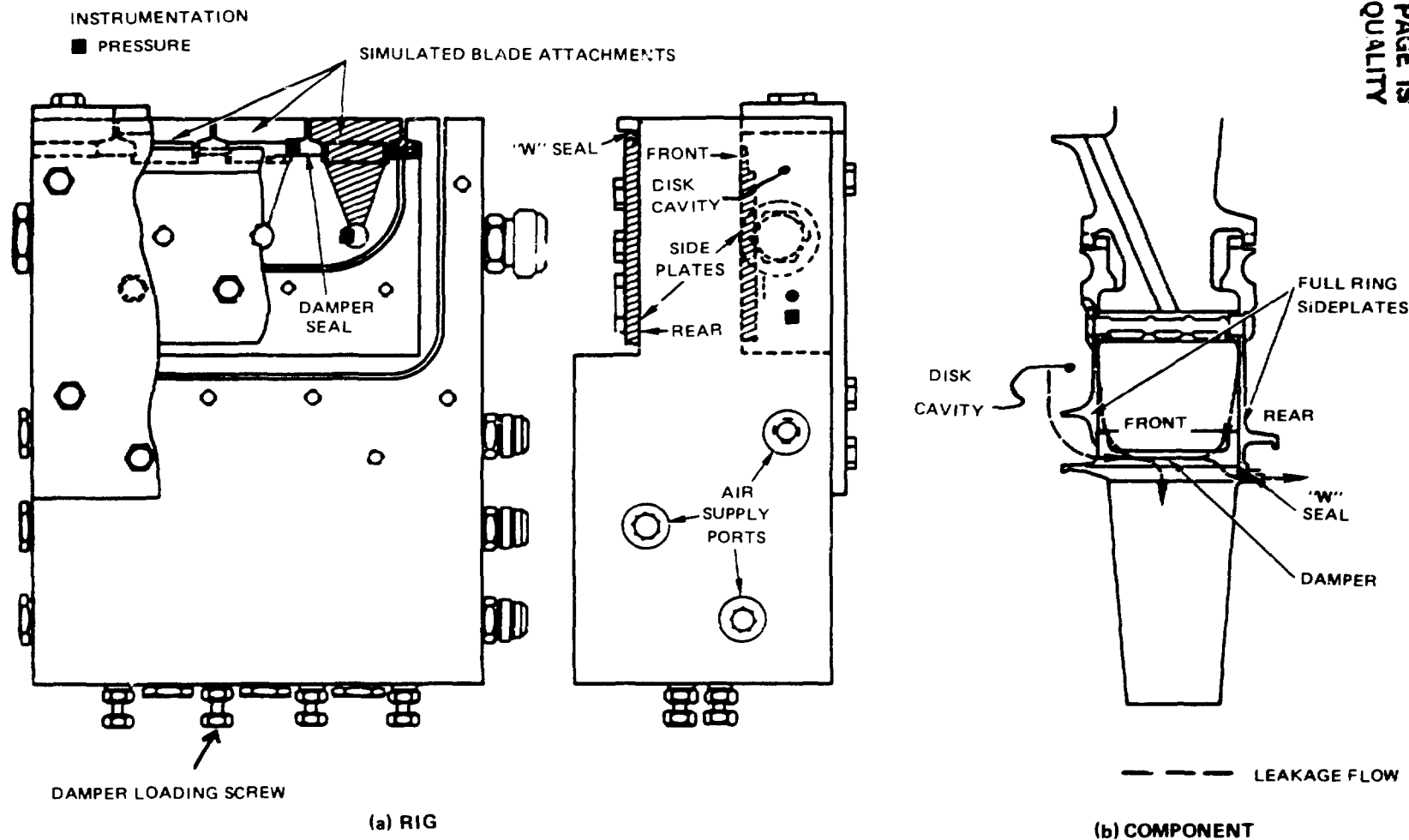


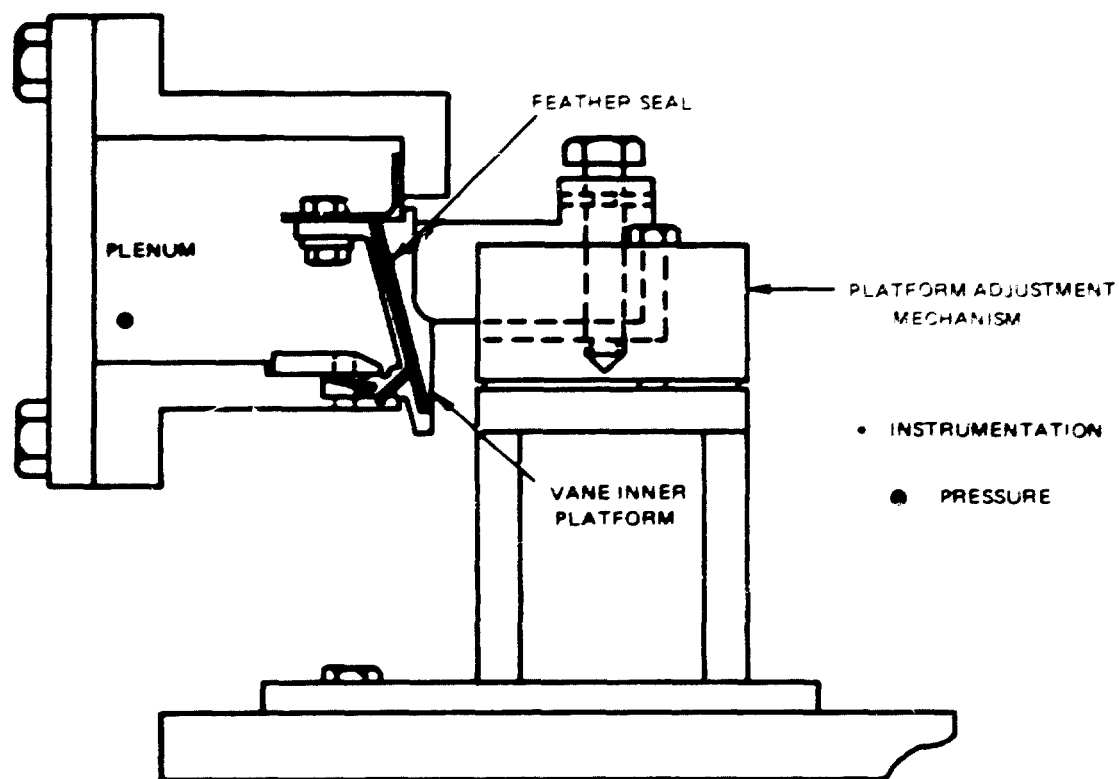
Figure 4 Energy Efficient Engine High-Pressure Turbine Blade Attachment Leakage Rig - Major components of this rig simulated the high-pressure turbine component design shown.

Sealing concepts chosen for evaluation included wire rope at the front attachment, feather seals between vane inner platform segments, and a combination of a feather seal and sheet metal "hook" at the inner diameter rear attachment to accommodate twist, rock, and tilt motions. These motions result from the large thermal gradients that can be experienced by the vane hardware in the engine environment. The potential increase in leakage area caused by these gradients is shown in Figure 6. The contact surface between the vane buttress and the rear case support is normally curved as shown by the dashed lines on Section B-B in Figure 6. With this kind of contact surface, vane tilt due to differential growth caused by thermal gradients will open up a leak path similar to that shown in Section A-A of the figure. This problem was solved by chordal cuts which converted the curved contact surface into a straight-line surface (shown again in Section B-B) that retained total contact between the mating surfaces when vane tilt occurred. Under these circumstances, no leak paths open up. The leakage rig was designed to simulate these motions so that the sensitivity of leakage flow through the resultant gaps could be fully investigated during the test program. Figure 7 illustrates the rig adjustments that could be made to impart these motions.

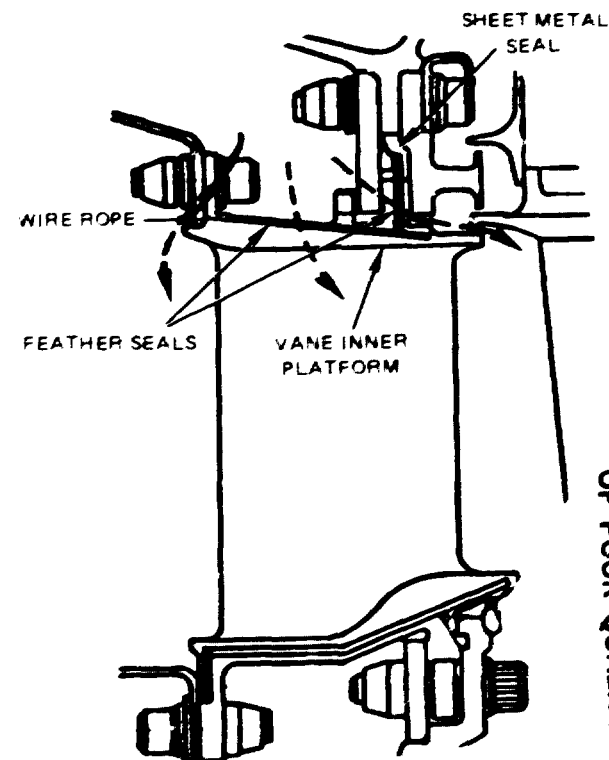
3.4 Vane Outer Attachment and Outer Air Seal Rig

This "combination" rig, designed to test sealing concepts for the outer diameter vane platform and outer air seal, is shown in Figure 8(a). As indicated, the total rig comprised two subassemblies: (1) an assembly to simulate the vane outer attachment and (2) an assembly to simulate the outer air seal, which was simply bolted to the vane outer attachment assembly. The vane assembly then provided a common plenum for both rigs. This design simulated the common source of leakage flow i.e., compressor discharge air in the combustor outer liner cavity for the two primary leakage sources modeled by the rig.

The major leak paths that this rig was designed to simulate are shown in Figure 8(b). For the vane outer attachment, flow from the combustor outer liner cavity leaks past the vane outer diameter from front attachment, between outer platform segment gaps, and past the vane outer diameter rear attachments. (This latter flow leaks to the gaspath through the gap between the vane outer platform and the outer air seal shoe). For the outer air seal, flow from the outer air seal cooling air supply cavity leaks between outer air seal shoe segment gaps and flow from the same supply cavity leaks past the junction of the outer air seal and the active clearance control rear support rail. Sealing concepts chosen for evaluation are indicated in Figure 8(b) and include wire rope at the outer diameter front vane attachment radially sliding joint and rear attachment chordal cut, feather seals between vane segment platform gaps and outer air seal segment gaps, and "W" seals at the junction between the vane outer diameter rear attachment and the active clearance control front support rail as well as the junction between the outer air seal shoe and the active clearance control rear support rail. The outer air seal shoes were designed to permit circumferential motion in order to simulate the constant change in spacing typical of outer air seal motion.



(a) RIG



(b) COMPONENT

Figure 5 Energy Efficient Engine High-Pressure Turbine Vane Inner Attachment Leakage Rig - Major components of this rig simulated the high pressure turbine component design shown.

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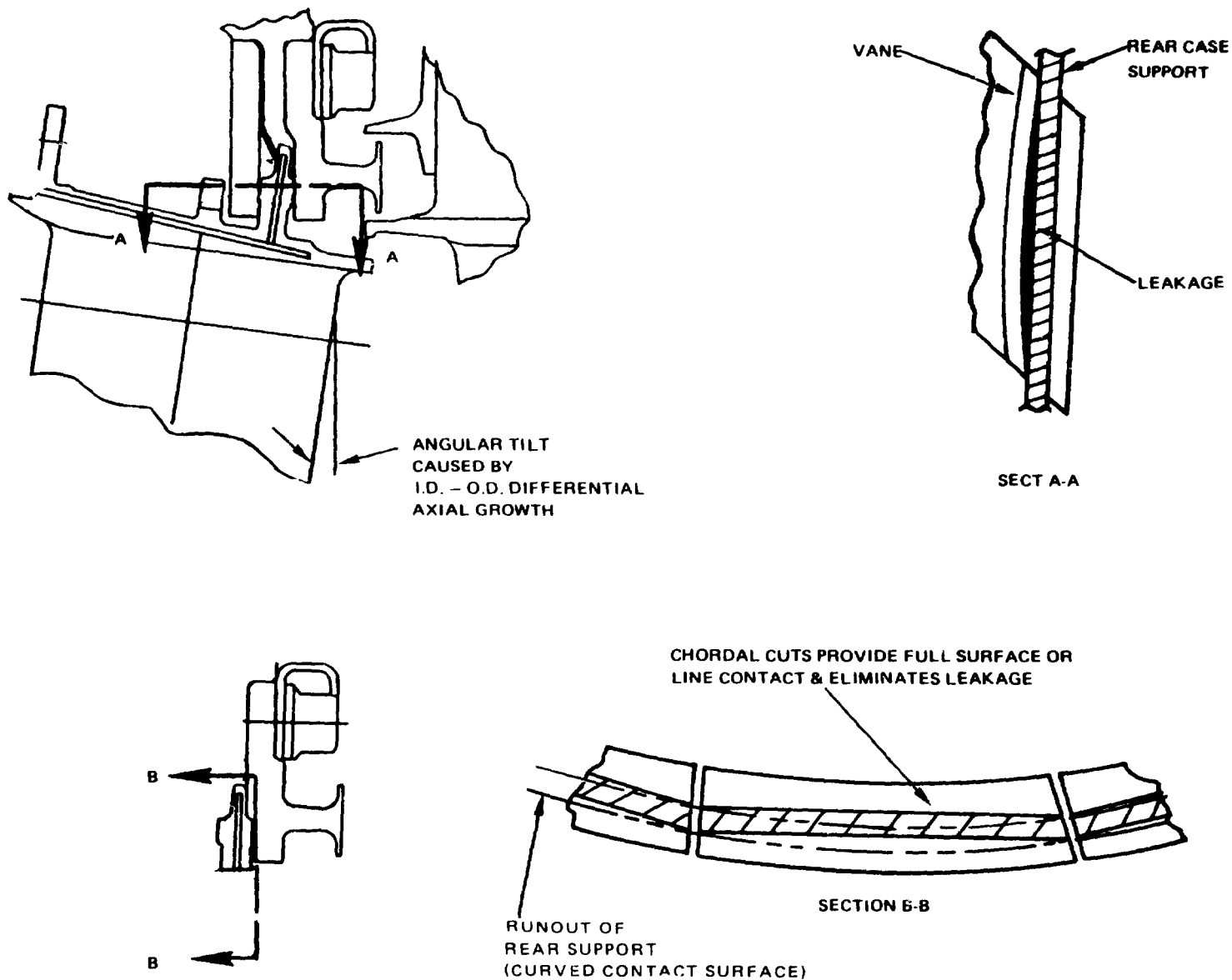


Figure 6 Vane Buttress Chordal Sealing Surfaces - The increased leakage paths caused by thermal gradients are shown.

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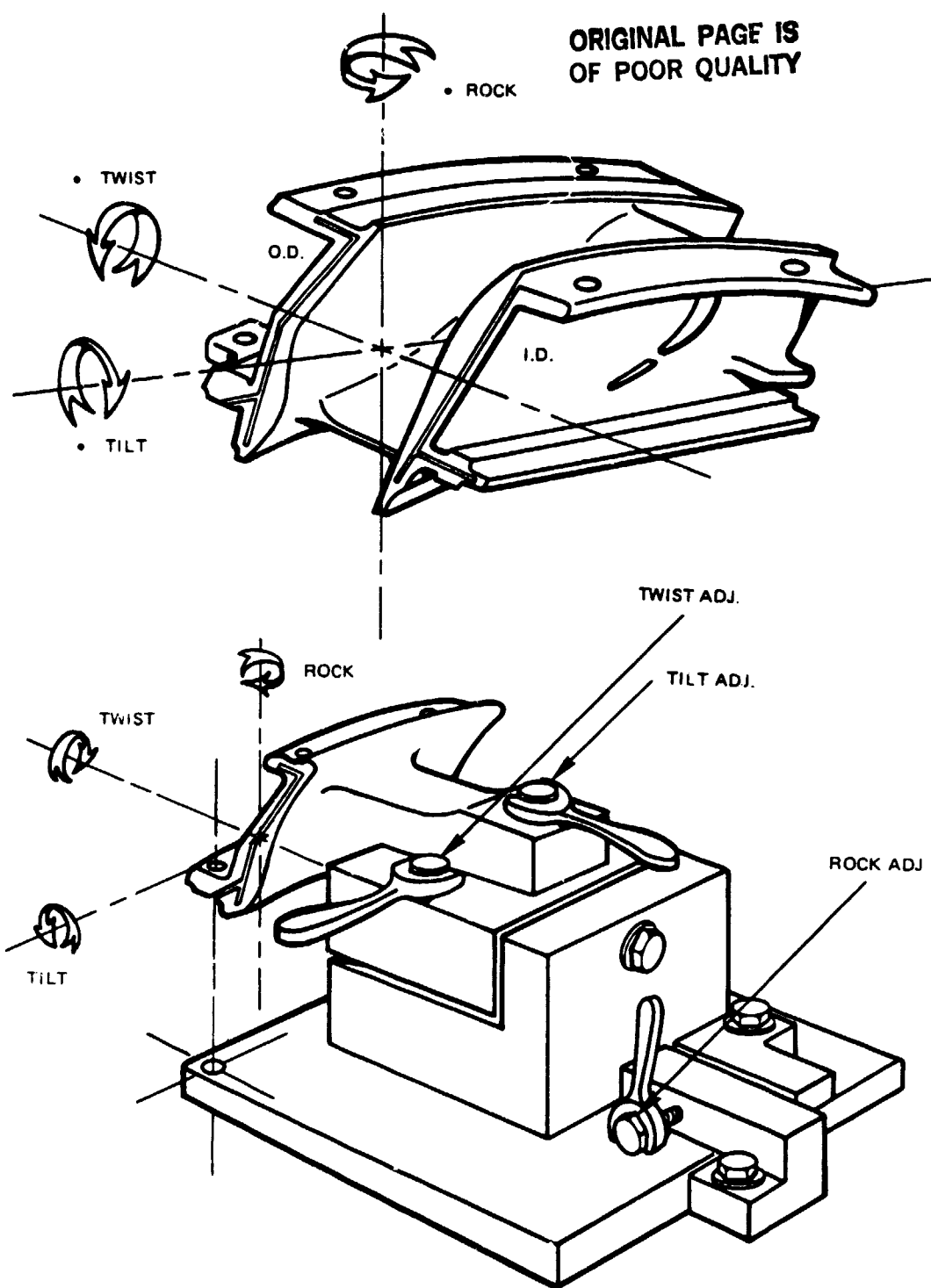


Figure 7 Energy Efficient Engine High-Pressure Turbine Vane Outer Air Seal Rig Vane Motions - Adjustment "jack screw" bolts and precision shims were used to impart motion. A repeatable, nominal vane position was established, and motions along major axes were measured relative to this position using precision dial indicator gages.

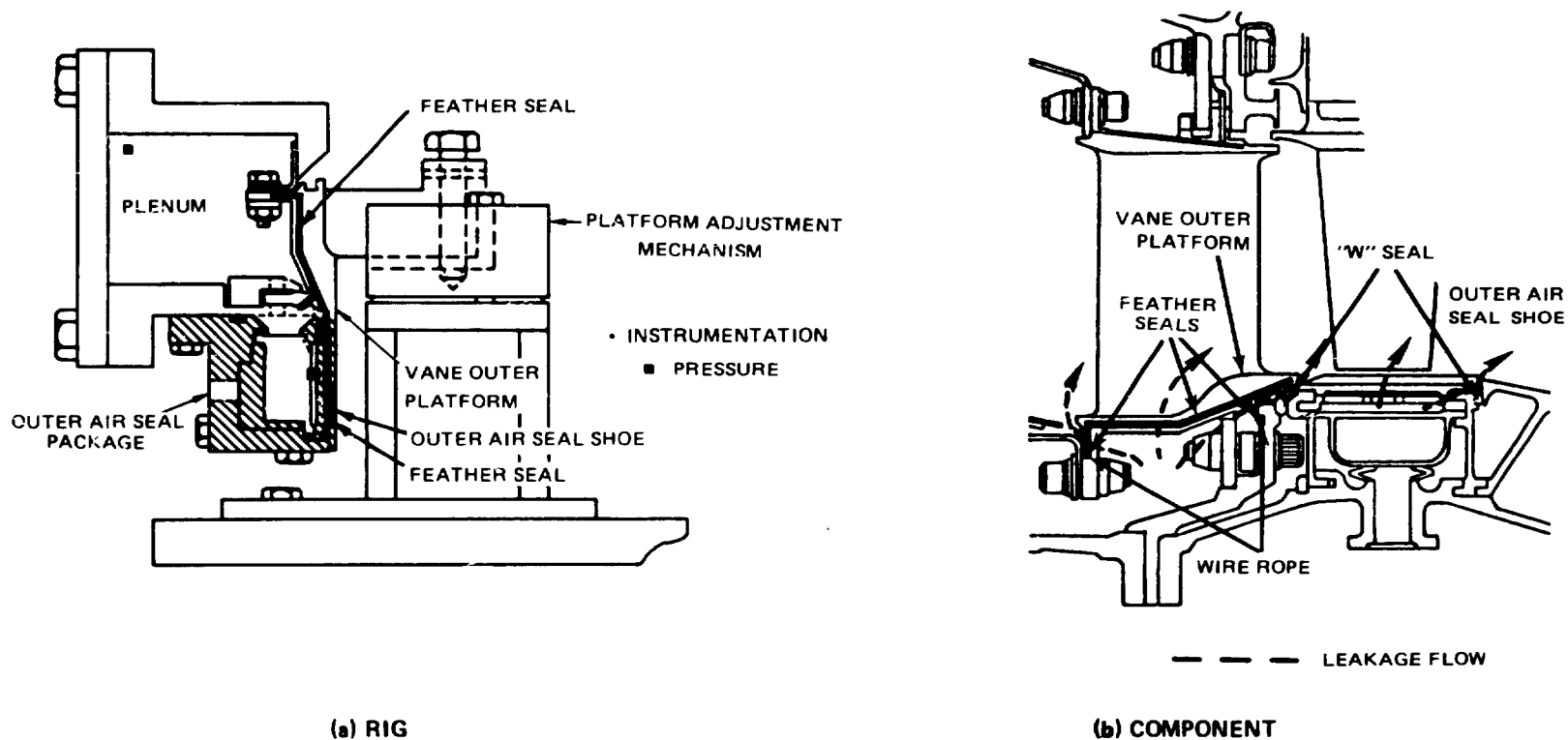


Figure 8 Schematic of Energy Efficient Engine Outer Diameter High-Pressure Turbine Vane and Outer Air Seal Rig - The outer air seal rig was an adaptation of the vane rig. Each configuration used the same support hardware, and both incorporated simulations of the platform interfaces for the high pressure turbine component design shown.

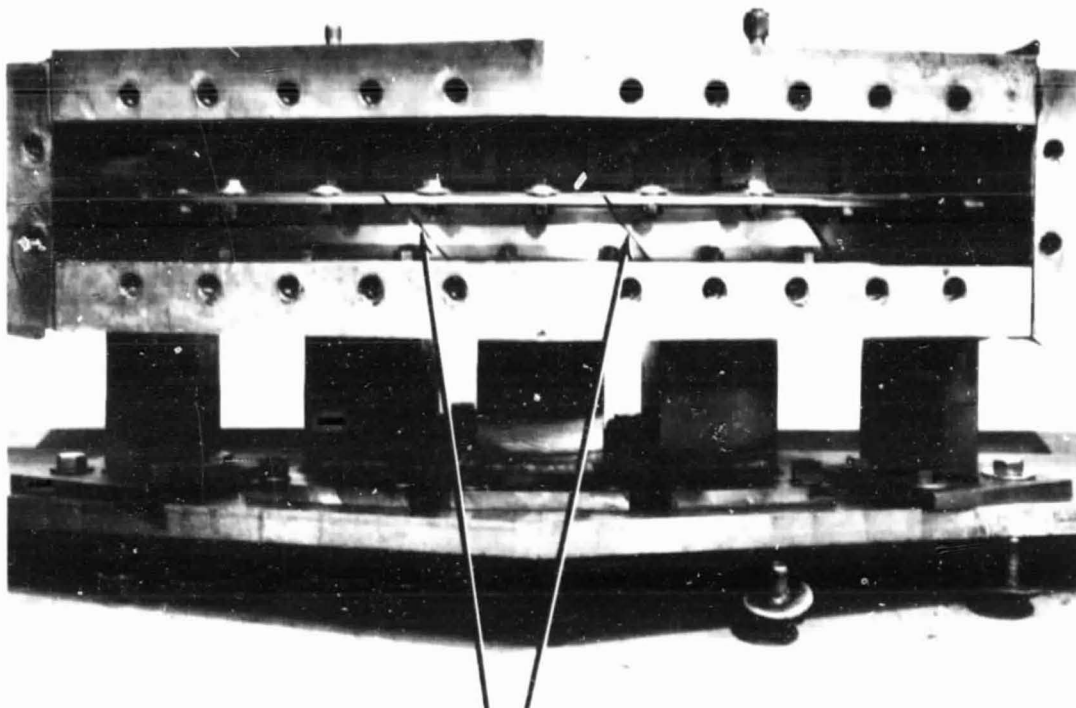
4.0 RIG FABRICATION AND ASSEMBLY

All of the test rigs were fabricated using conventional materials. In the assembly of the rig, a "building block" approach was used in which the subassemblies representing the leakage sources were mounted to a common support hardware base.

A typical rig assembly sequence is described using the blade attachment rig as an example. Blade platforms were assembled with the platform gaps set by feeler gage. Once bolted in place, the final machining was completed on the rear surface and front surface in conjunction with the blade attachment "firtree" contour. Once the blades were gapped and machined, there was no need for them to be adjusted during testing. Next, the rear sideplate, with the "W" seal inserted, was bolted in place. Positioning was accomplished by setting the gap between the top edge of the sideplate and the blade overhand. The dampers were then forced back against the rear sideplate and radial loading applied. The front sideplate was gaged in a manner similar to the rear and then the front plenum cover was bolted into place. Vane and outer air seal rig assembly was similar to that of the blade attachment rig. Feather seals were located only in the center two platform gaps; the outer platform gaps between the movable vanes and the stationary plenum were sealed with rubber gaskets.

Since these rigs were experimental devices, it was important that extraneous leak paths be isolated and sealed so that close control could be maintained over leakage (i.e., damper loading screws might leak through the threads between the bolt and the sealing nut). Consequently, each rig assembly underwent a thorough leak check when assembly was completed and extraneous leak paths were sealed. Examples of a fully assembled rig are shown in Figures 9, 10, and 11.

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FEATHER SEAL LOCATIONS

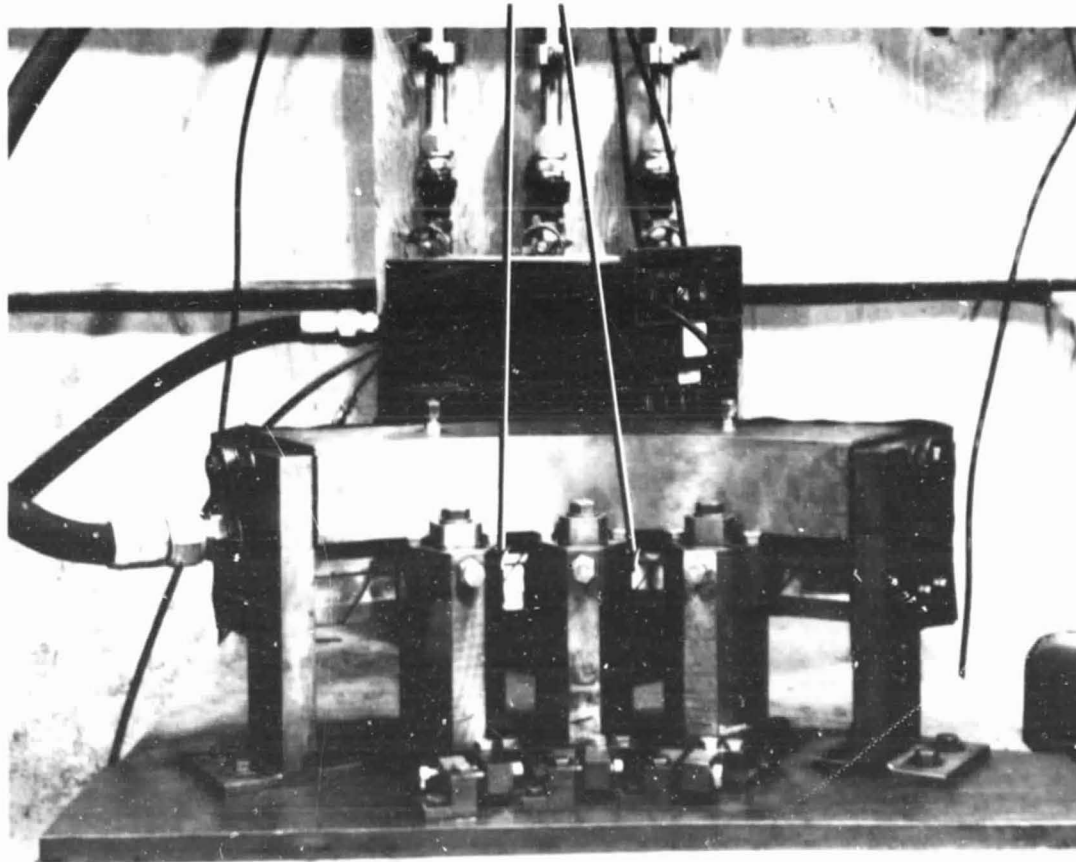


Figure 9 Rear (Top) and Front (Bottom) View of Vane and Outer Seal Leakage Rig - The feather seal locations can be seen along with attendant test hardware.

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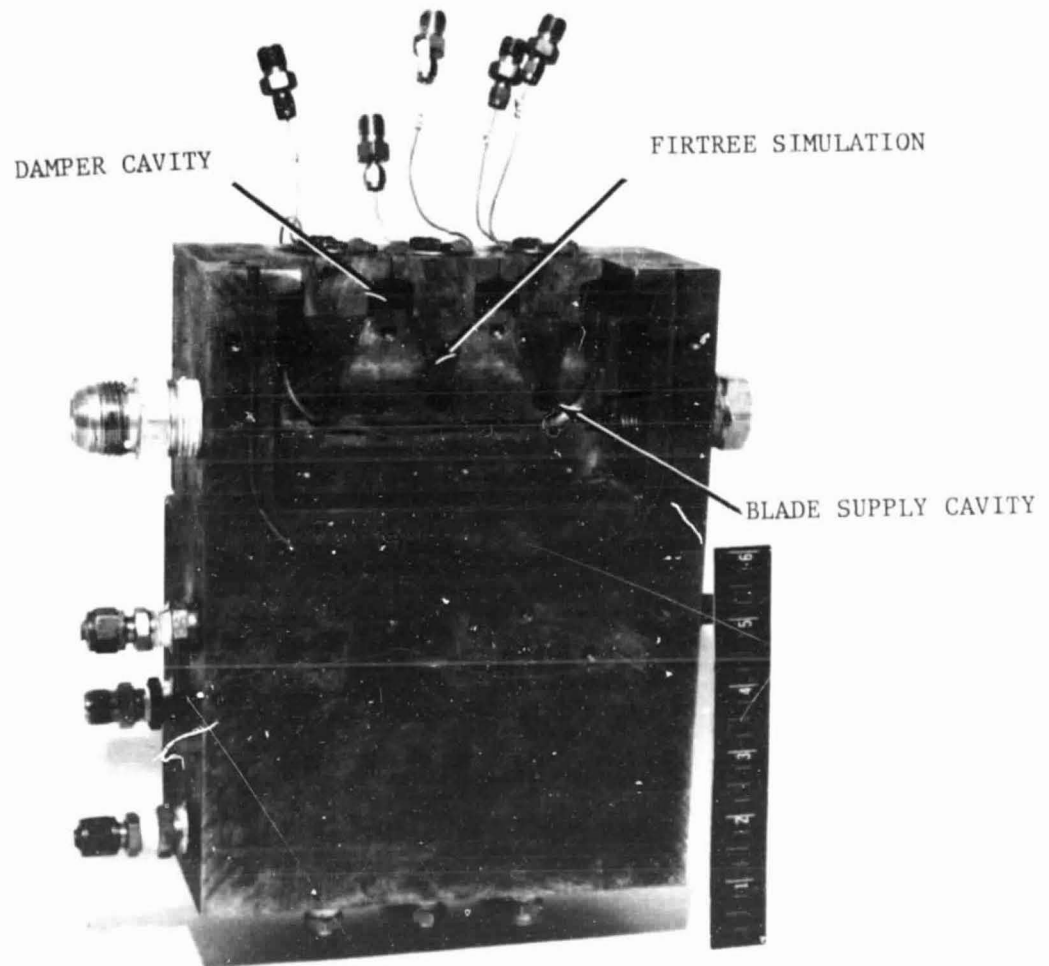


Figure 10 High Pressure Turbine Blade Attachment Disk Cavity with
Front Sideplate Removed

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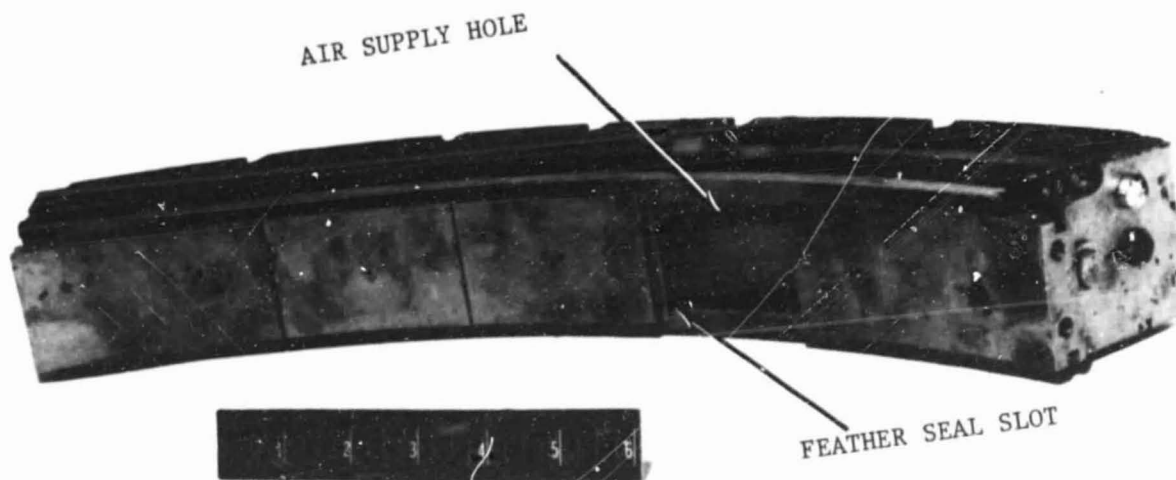


Figure 11 Outer Air Seal Leakage Package with One Shoe Removed

5.0 TESTING

5.1 General Description

The basic purpose of the test effort was to provide the data necessary to determine accurately the best leakage control concepts to be used in the detailed design of the high pressure turbine component. This determination required the accurate measurement of leakage flow rates through the various leak paths and the documentation of leakage flow parameters over pressure ratio ranges comparable to those which might be expected in the turbine component operating environment.

Leakage testing covered a range of pressure ratios (leakage flow rates). Rig exit conditions were held constant and inlet (supply) pressure was varied through the use of control valves. Coolant flow ratio, temperature, and static and total pressure measurements were taken at each test condition. Each leakage path was systematically sealed off to determine its contribution to overall leakage. Areas where high leakage occurred were redesigned and retested to verify leakage reduction.

Accomplishing the above required adequate test facilities and instrumentation, specific test objectives and procedures, and a logical approach to data acquisition and data reduction. These are described in the following sections.

5.2 Test Facility and Instrumentation

Test Facility

All testing was conducted in test stands X-914 at the Pratt & Whitney Aircraft Middletown Facility and X-108 at Pratt & Whitney Aircraft in East Hartford. The pressure, flow capacity, and instrumentation capability of these facilities complied with all program requirements. Facility compressors supplied the air to operate the component. This air supply was controlled by throttling valves and was metered by standardized choked nozzle or orifice plate measurement procedures.

Instrumentation

The primary performance instrumentation for the rig consisted of intermediate pressure taps along certain leakage paths. Various pressure measuring devices were used. Downstream or "dump" pressure was measured in all testing. Instrumentation to measure leakage flow rates included an orifice flow meter (blade attachment rig) and a sonic nozzle meter (vane rig). The latter measures flow by using a choked convergent-divergent nozzle. A non-dimensional flow can then be deduced by looking at the ratio of upstream to downstream pressures.

The instrumentation provided the necessary information to calculate flow rates and pressure drop characteristics for each of the leakage paths and sealing concepts evaluated in the rigs. A complete list of instrumentation for the rotor attachment rig is listed in Table 1. Instrumentation for the vane leakage rig is presented in Table 2.

TABLE 1
BLADE LEAKAGE RIG INSTRUMENTATION

<u>Location</u>	<u>Type</u>	<u>Quantity</u>
Air Supply	Orifice	2 (Upstream, Downstream)
Blade Supply Cavities	Static Pressure	6 (1 per front and rear cavities)
Damper Cavities	Static Pressure	4 (1 per cavity)
Front Disk Cavity Plenum	Static Pressure	1

TABLE 2
VANE LEAKAGE RIG INSTRUMENTATION

<u>Location</u>	<u>Type</u>	<u>Quantity</u>
Air Supply	Choked Venturi	2 (Upstream, Downstream)
Rig Plenum	Static Pressure	2
OAS Feed	Static Pressure	2

5.3 Test Procedures

5.3.1 Shakedown Testing

During assembly, all instrumentation was installed, identified, and connected. In addition, pressure checks on all pressure sensing instrumentation were completed. Shakedown testing consisted of obtaining a complete data point to substantiate the mechanical integrity of the test rig and to verify the performance of the instrumentation and data acquisition systems. The performance test program was begun after it was determined that all instrumentation and systems were operating properly.

5.3.2 Performance Testing

5.3.2.1 Blade Attachment Rig Testing

The major activities and goals associated with the blade attachment rig test effort were to:

- o Test the range of pressure ratios for each test configuration,
- set pressure ratio and measure leakage,
- o Simulate side plate deflection,
- o Determine the sensitivity to "W" seal leakage,
- o Isolate damper leakage,
- o Modify sideplate, dampers, etc. as required to provide an adequate cooling flow

Table 3 presents the planned test conditions for the rotor attachment rig. Here, maximum rig pressure as measured on the sideplate was to be 40 psi absolute. Maximum flow through any of the three air supplies is estimated as 0.02 lbm/sec at ambient temperature.

TABLE 3

BLADE LEAKAGE TEST PROGRAM

<u>Operating Condition</u>		<u>Description</u>
1	Base	(Each operating condition consists of multiple data points. Each includes an evaluation of the various leakage paths in order to appraise the impact of the particular geometry change)
2	Deflected Side Plates	
3	More Flexible "W" Seal	
4	"Sealed" Damper Leakage	
5	Metering Hole in Damper (If additional air required for cooling)	

Pressure versus flow plots were to be obtained for five leakage paths: (1) front sideplates, (2) rear sideplates, (3) through the front of the damper, (4) around the damper, and (5) the W-seal. Some method of isolating these last two paths from each other appeared necessary. It was determined that the effective area of the leak past the damper could be determined just once, after which the damper leaks could be "subtracted out" from overall flows. In light of this, the first testing incorporated a positive seal beneath the rear sideplate, thereby eliminating the W-seal leak and leaving only the damper leakage path to ambient pressure.

Under engine speed conditions (13,000 rpm), the centrifugal force applied to the damper approximates one ton; a force more than adequate to "seat" the dampers against the blade attachments. This force could not be simulated in the rig because the compressive stress in the damper adjustment rods (over 80 ksi) would exceed their capability. Consequently, leakage flows were measured at different damper loadings (up to 250 lbf. per rod) to determine at what loading they "seated" (ie. a loading level beyond which the effective leakage area around the damper remains essentially constant). The loading, thus determined was an accurate simulation of engine speed induced loadings. When necessary, the dampers were reset each time the rear sideplate was moved.

The planned testing sequence was as follows:

1. Shakedown and Parasitic Leak Plugging - Completely assemble rig, flow all three sources, and check for leaks. Modify and seal where necessary. Check uniformity of pressure in supply cavities and damper cavities. Any non-uniformity must be accounted for either by sealing parasitic leaks or by otherwise taking it into account. Determine torque requirements for the dampers. The small holes in the front of the dampers should be plugged for this and subsequent tests.
2. Damper-Platform Contact Surface Leak - Starting with the rig as arranged above, set the dampers, then remove the rear sideplate and W-seal. Do not move the dampers. The sideplate, without the W-seal, is repositioned with a gasket completely covering the inner face. Then, without resetting the dampers, flow only the front cavity.
3. Damper Front Entrance Flows - Return the rear sideplate to the normal configuration with the W-seal in place. Reset the dampers. Flow only the front cavity. Unplug damper holes and reset dampers if they have been moved; then reflow.
4. Unshimmed Sideplate and W-Seal Flows - The rig remains as in the previous test. However, only the front and rear sideplate supplies were flowed. Pressures are balanced in the front and rear supplies. Pressures are also equal in all four damper cavities. The leakage in this test represents the leaks of three blade units (unlike the No. 2 test, which represented four blades).
5. Shimmed Sideplate Flows - This test is the same as the previous test, however, the sideplates are shimmed to simulate predicted engine gaps. A sideplate is shimmed so that either the entire sideplate is elevated, or it is wedged off the supply holes while maintaining hard contact at the top edge. Both techniques are tried. Shim sideplates so that their elevation off the base plate at the supply hole is one, two, and four mils. For the

wedged sideplate, also test with the W-seal removed. Dampers remain as they were set for test No. 4; do not reset when sideplate is shimmed. Flow only the front and rear supplies.

6. Curved Sideplate Flows - Rework the front and rear sideplates as indicated in Figures 12 and 13. Install these in a wedged position, with shimmed one mil gaps at the supply cavities. Reset dampers. Flow only the front and rear supplies. Shim to two mils and repeat.

Test procedures followed the plan. W-seal testing was de-emphasized when preliminary results showed it had little effect in the rig.

Although the original intention of the test program was to run the rig by flowing as many as three independent supplies simultaneously (front and rear sideplates, and damper front entrance), it was decided that the central location of the blade neck cavity could be exploited. It acted as a supply plenum for the damper and W-seal flows and as a dump for flow up the sideplates. As a consequence, all tests were run with only one supply flowing at a time, either to or from the damper cavity. The flow paths modelled by the rig were split quite naturally into five mutually exclusive areas for analysis.

5.3.2.2 Vane Attachment and Outer Air Seal Rig Testing

The major activities and goals associated with the vane attachment and outer air seal rig test effort were to:

- o Test the range of pressure ratios for each test configuration,
 - Set pressure ratio and measure leakage,
- o Determine the vane movements which have the largest impact on leakage,
- o Isolate a leakage area by selectively sealing that area,
- o Evaluate various sealing configurations,
- o Evaluate feather seals (single and in series),
- o Evaluate "W"-seals,
- o Evaluate wire rope,
- o Evaluate sheet metal seals.

Table 4 shows planned test conditions for the vane and outer air seal leakage rig. The inner diameter is tested separately in the same sequence. For testing purposes, the vane leakage will be considered as three separate areas: front attachment, rear attachment, and feather seals.

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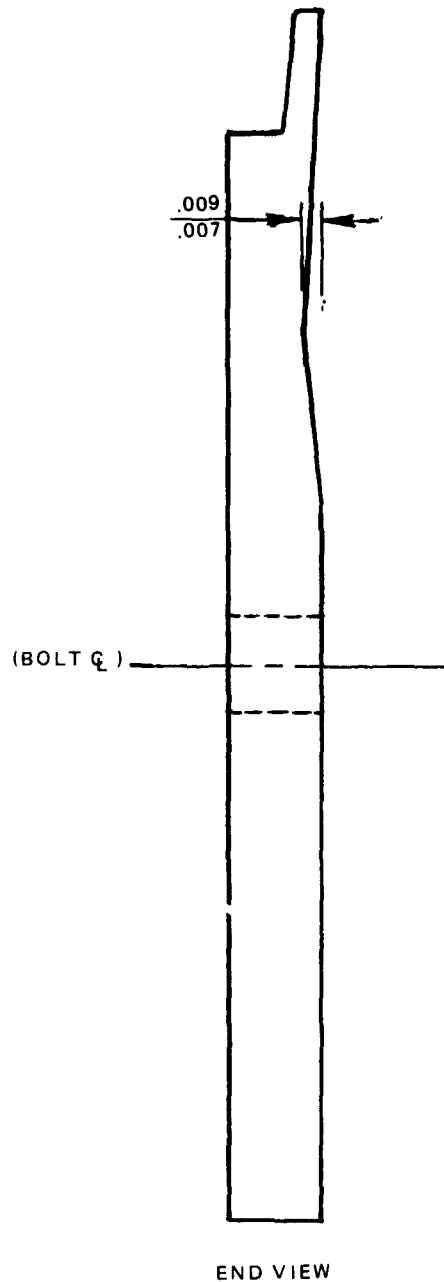


Figure 12 Modification of the Front Sideplate Deflected Shape for Rotor Rig Testing (Dimensions in Inches)

TABLE 4

VANE LEAKAGE TEST PROGRAM (OD and ID)

<u>Operating Condition</u>	<u>Description</u>	<u>Align</u>	<u>Tilt</u>	<u>Rock</u>	<u>Twist (2)</u>
1	Base (without OAS)	X	X	X	X
2	Seal Front Attachment	X	X ¹	X ¹	X ¹
3	Seal Rear Attachment	X	X ¹	X ¹	
4	Seal Platform (Multiple Fits)	X	X ¹	X ¹	
5	Base (O.D. Plus OAS)	X	X ¹	X ¹	
6	Radially Displaced OAS	X	X ¹	X ¹	
7	Seal OAS Component Interfaces	X	X ¹	X ¹	
8	Optimized Configuration Test	X	X ¹	X ¹	

- Note: 1) May be omitted if baseline testing demonstrates minimal impact on leakage.
- 2) Twist was subsequently eliminated from the test program when it was found that the leaks caused by imparting a twisting motion to the rig could not be accurately isolated or quantified.

Vane Attachment Testing

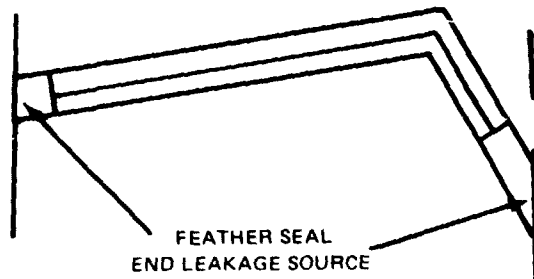
When initial test results indicated excessive feather seal leaks, efforts on the vane rig were concentrated on developing an acceptable feather seal configuration (see section 6.2.1.1). Accordingly, the test plan was modified and testing concentrated on the evaluation of specific feather seal configurations in the vane outer diameter platform. Testing of the inner diameter attachment was not conducted because it was felt that results from the outer diameter testing would be applicable to the inner diameter feather seals as well.

The general test procedure was to hold constant pressure ratio across the feather seals along their length and then simulate lengthwise pressure ratio variations by sequentially adjusting this constant (see section 5.4). Next, selectively close off end leaks to isolate feather seal leakage by plugging the end gaps as shown in Figure 14(b). Figure 14(a) illustrates the leakage sources that were sealed by this method.

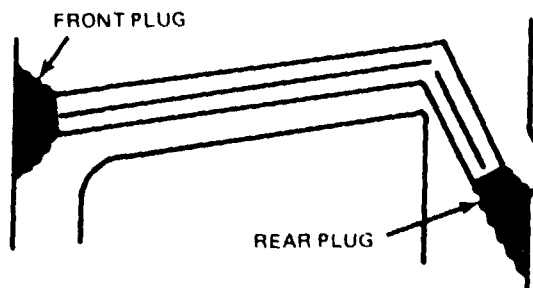
The average platform gap assumed for these tests was sixty-three mils (measured along the arc of the platform). This was considered high, but rig construction made it difficult to reduce.

The specific procedural sequence used in testing the various feather seal configurations was as follows:

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(a) FEATHER SEAL WITHOUT END PLUGS



(b) FEATHER SEAL WITH END PLUGS

Figure 14 Vane Rig Feather Seal Plugging Scheme - The intent of this scheme was to selectively close off the end leaks; the position of the rear plug was such that it prevented the rear feather seal from seating.

1. Two-piece feather seal with overlap and electro-discharge machined (EDM) slot - Install 10 mil thick feather seals and obtain flow vs. pressure ratio with no end plugs installed. Repeat procedure with front plug installed and then with both front and rear plugs installed. Remove 10 mil thick feather seals and replace with 20 mil thick feather seals. Repeat complete procedure.
2. Remove simulated platform with EDM slot and replace with simulated platform with ground slot. Install 10 mil thick feather seals and obtain flow vs. pressure ratio with no end plugs installed. Repeat procedure with front plug installed and then with both front and rear plugs installed.
3. Using same platform as in Step 2, plug short overlap section of long feather seal slot with epoxy to eliminate overlap. Install 10 mil thick feather seals and obtain flow vs. pressure ratio with no end plugs installed. Repeat procedure with front plug installed.
4. Using same platform as in Step 3, remove 10 mil thick feather seals and replace with 20 mil feather seals. Obtain flow vs. pressure ratio with no end plugs installed. Repeat procedure with front plug installed.
5. Using same platform as in Step 3, remove short feather seal and replace with a modified short 10 mil feather seal with a crook in it. (This replacement might require some reworking of the feather seal slot at the intersection to accommodate the extra thickness.) Obtain flow vs. pressure ratio with no end plugs. Repeat procedure with front plug installed. Next, remove two-piece feather seal and replace with single, long 10 mil feather seal curved to fit the slot previously occupied by the short feather seal. Obtain flow vs. pressure ratio with no end plugs. Repeat procedure with front plug installed.
6. Remove single-piece feather seal and replace with two-piece 20 mil thick feather seal. Plug both front and rear and obtain flow vs. pressure ratio. Remove feather seals and rework slots so that they are ground through the ends of the platform. Install lengthened 10-mil thick feather seals, "blank" off feather seal slot ends and obtain flow vs. pressure ratio.
7. Re-install this platform used in Step 3 and insert 20 mil thick feather seals in slot. Simulate vane "rocking" motion in the rig and obtain flow vs. pressure ratio with no end plugs. Repeat the procedure; first with the front plug installed and then with the rear plug installed. Manually displace feather seals if necessary to achieve desired displacement effects.

8. Remove the 20 mil thick feather seals from the configuration used in Step 7 and replace with 10 mil thick feather seals. Holding the choked-flow pressure ratio constant, simulate varying degrees of vane tilt and measure leakage flow. (The basic procedure here was first to simulate the tilt then "jiggle" the rig until the measured flow reached a minimum; i.e., the seals had seated in the slot. Momentarily unseat or rotate the seals by pushing on them through the platform gap and again measure leakage flow).

In general, test pressure ratio covers the range from unity to choked flow levels. The test sequence first measures leakage for all of the major leakage paths, with successive sealing of individual leaks. The difference between two succeeding tests yields the sealed leakage.

Outer Air Seal Testing

The proposed program for outer air seal testing was as follows:

1. Base Configuration - With the vane outer diameter platform gaps and flanges sealed, assemble the outer air seal. By alternate sealing, obtain flow versus pressure through the platform gaps and through the wire rope seals.
2. Base Configuration (No Sealing) - Repeat step 1 removing all wire rope seals and the feather seal.
3. Platform Gap Sensitivity - With wire rope and feather seals installed, obtain total flow versus pressure for various adjustable outer air seal platform gaps.

Leakage levels for the blade outer air seal were established by injecting cooling air through the rig without feather seals. The shoes were initially tested with the gap between the segments tightly closed. The gap was then progressively widened to 0.040 inch. Following this sequence, the procedure was repeated with feather seals in place.

Wire rope, originally planned for use in sealing four internal locations in the outer air seal, was omitted from the test program when it became obvious that it could not provide the required sealing. Attempts to acquire a satisfactory wire rope were unsuccessful, and the probability of obtaining or developing one with the necessary thermal and mechanical requirements seems improbable without a significant development program (see discussion, section 6.2.3).

5.4. Data Acquisition and Reduction

Data Acquisition

All test data were recorded directly in engineering units. Pressure data were acquired using a precision transducer and a digital readout gage, or a manometer. A sampling of the data were processed at the test stand to verify the data accuracy and validity. See section 3.3.2, "Instrumentation," for more details on the actual instrumentation hardware.

Data Reduction

Data from the leakage tests were reduced to flow parameters as a function of pressure ratio (plenum to discharge) for each major leakage path. To achieve this, leakage characteristics were evaluated at the local pressure ratio anticipated in the engine along each path and then analytically summed to predict the total leakage flow. This procedure is shown schematically for one of the vane inner platform feather seals in Figure 15. The leakage flow versus pressure ratio characteristic obtained in the rig for the entire feather seal could be used to calculate leakage for individual sections subjected to different pressure ratios in the engine. This analytical technique was previously substantiated by comparing such calculated leakages with actual leakage measurements in a vane cascade. Gas path flow through the cascade ensured the proper local pressure ratio for each leakage path.

Composite leakages were determined following this procedure in order to determine anticipated engine leakage levels for the rotor attachment, vane platform/attachment, and blade outer air seal. The results of this data analysis were used to isolate high leakage areas requiring redesign and retest.

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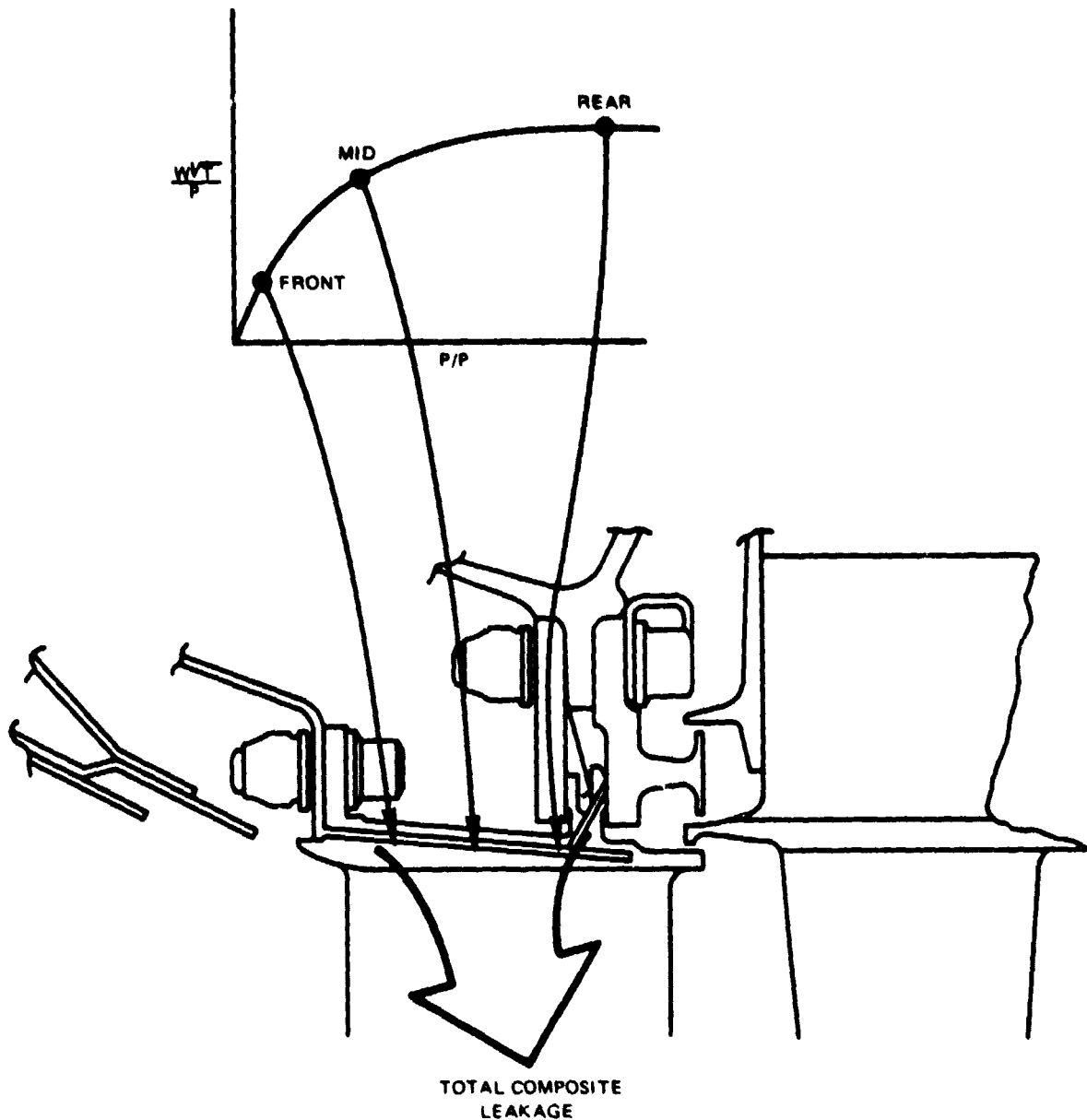


Figure 15 Data Reduction and Analysis - Leakage characteristics were evaluated at the local pressure ratio anticipated in the Energy Efficient Engine for each path to analytically predict the total leakage flow.

6.0 RESULTS

6.1 Disk-Blade Attachment Rig

During testing, the five major leakage sources associated with disk-blade attachment were isolated and evaluated. These were (1) damper entrance leakage, (2) blade gap/damper leakage, (3) front sideplate leakage, (4) rear sideplate leakage and, (5) "W" seal leakage. Results of these tests are discussed in the following sections.

In some cases, tests were conducted at higher than predicted pressure ratios in order to obtain valid test results. These test results could be extrapolated, where appropriate, into the predicted pressure ratio range. In other cases, predictions do not agree with test results because the assumptions used in the predictions were based on actual engine experience not simulated in the rig. No attempt was made, in this supporting technology program, to modify the predictions based on subsequent test results.

Damper Entrance

Component design studies indicated that, under certain conditions, hot gas could leak into the blade neck cavity from the flowpath. This situation could happen, for example, if cooling flow into the cavity were not sufficient to maintain a static pressure in the cavity equal to or slightly above that in the flowpath. Consequently, two damper entrance seal configurations were evaluated; one with a small hole in the damper front plate to provide additional cooling flow area and one without this hole.

The test results shown in Figure 16 indicate that the leakage characteristics of the configuration were not significantly affected by the presence of the flow hole. This insensitivity might be expected since the pressure ratio across the damper entrance ($P_{\text{FRONT}} - P_{\text{DAMP}}$) is very low relative to the downstream pressure ratio ($P_{\text{DAMP}} - P_{\text{REAR}}$); this fact makes the flow level somewhat insensitive to variations in flow hole area for the hole side considered.

The slightly higher than predicted flow is due to parts tolerance variations in the rig which resulted in higher flow areas than those assumed in the prediction.

Blade Gap/Damper:

Flow from the blade neck cavity will leak out between the damper and platform and go out through the blade gaps. This leakage flow was measured. Test results in figure 17 show that leakage flow from the blade gaps was very low; significantly below predictions. The controlling element here was the degree of contact of the outer

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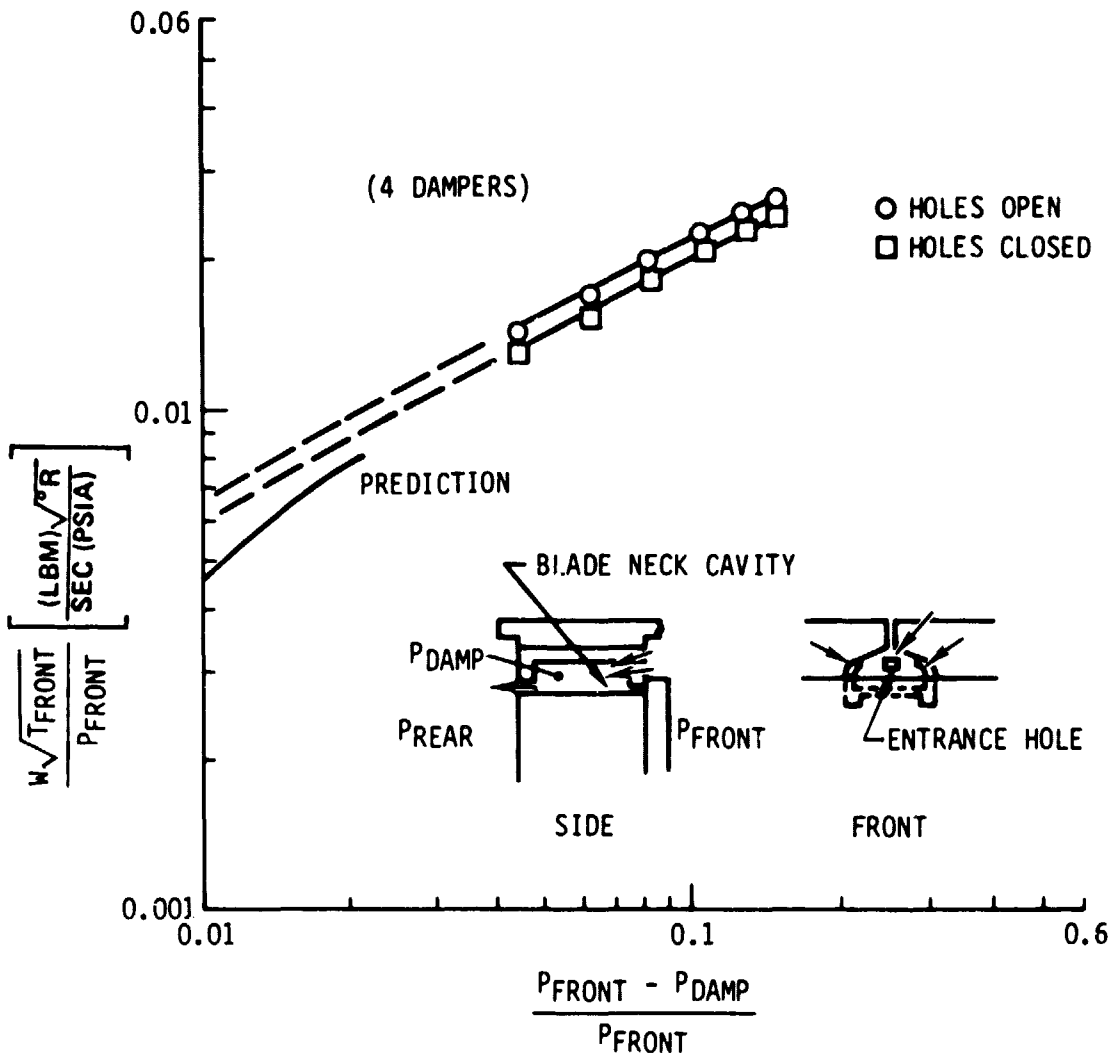


Figure 16 Damper Entrance Test Schematic and Data - The test results indicate that the leakage characteristics of the configuration are not significantly affected by the presence of a flow hole.

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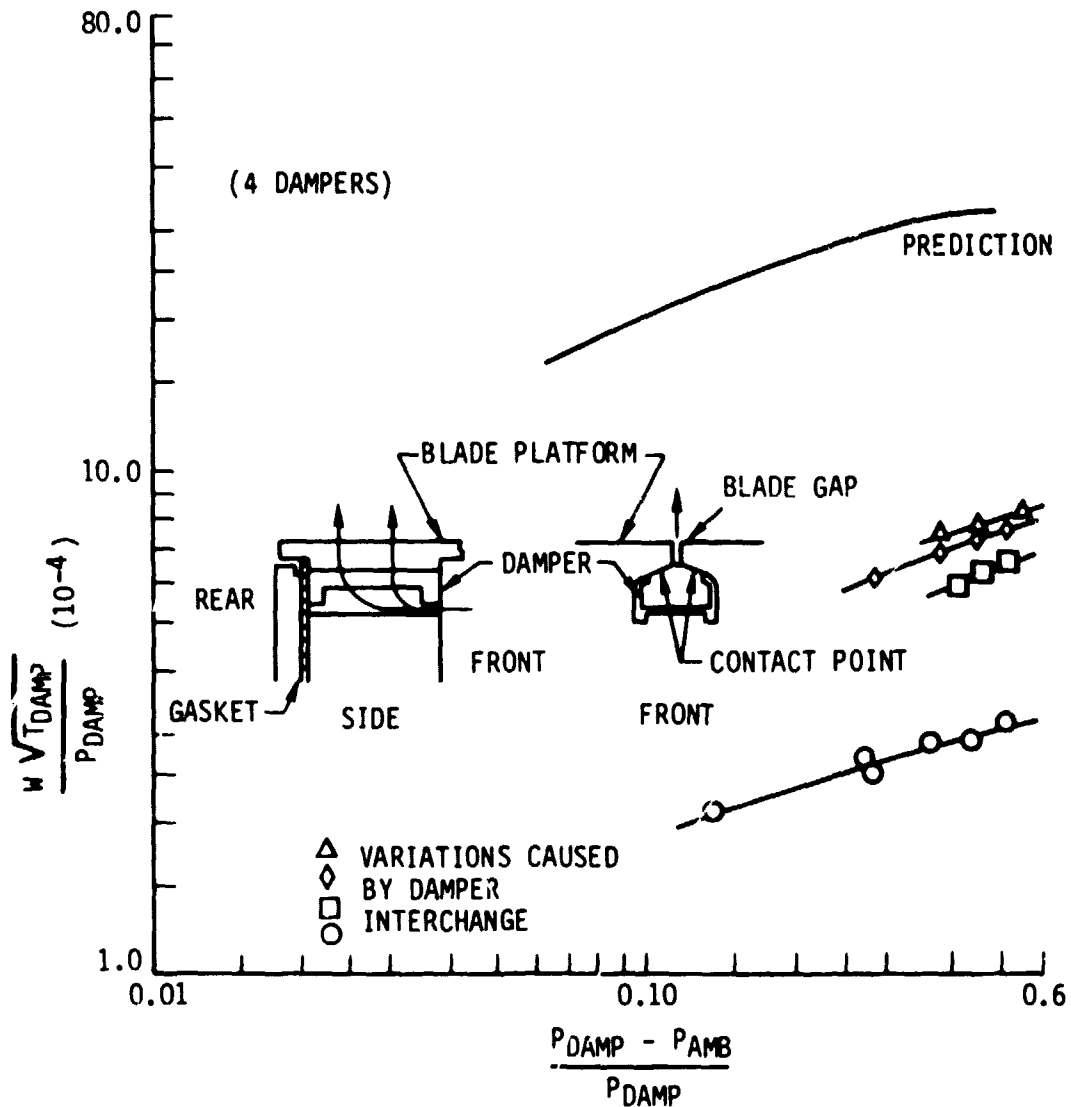


Figure 17 Build-to-Build Leakage Variation in the Damper, Test Schematic and Results - Flow from the blade gaps was very low despite damper tolerance variations.

surfaces of the damper - the "roof" - against the blade platforms. Interchanging dampers between cavities, in order to assess the effects of manufacturing tolerances and damper seating characteristics on leakage flow, resulted in significant variations in flow, although absolute flow levels remained comparatively low. This variation is probably due to waviness or lack of flatness at the damper "roof"-blade platform contact point, typical of manufacturing tolerances.

Interchanging dampers did not appear to affect their seating characteristics probably because of the smooth surface finish which characterized rig dampers. It is conceivable that relative motion between the blades and the dampers, as would occur under engine conditions, would increase the leakage flow by preventing the proper seating of the surfaces. However, smooth, flat surfaces, as were largely achieved on the rig, should minimize such an effect.

After the rig was built, there was a change in the design of the component blade root attachment which required a damper of considerably less mass than the one simulated in the rig. This change raised the concern that the damper might not properly "seat" under the centrifugal loadings imposed by turbine rotor speed. Informal testing showed, however, that leakage flow was independent of load, once the damper was properly positioned. Therefore, the rig data are expected to be applicable to any non damper/seal design which retains similar full-length sealing surfaces and has properly positioned seal/dampers.

Front Sideplate:

In a typical engine blade-disk attachment, gas loads on the blade force the blade root attachment back against the rear sideplate. This generally opens up a small gap between the front sideplate and the front side of the blade root attachment. The result is a finger-shaped leakage path up the front side of the disk, originating in the blade root cavity. This path was simulated in the rig by machining the thickness of the rig blade root attachment to be .005 inches less than that for the disk and by assuming a trapezoidal shape for the blade root attachment as shown in Figure 18.

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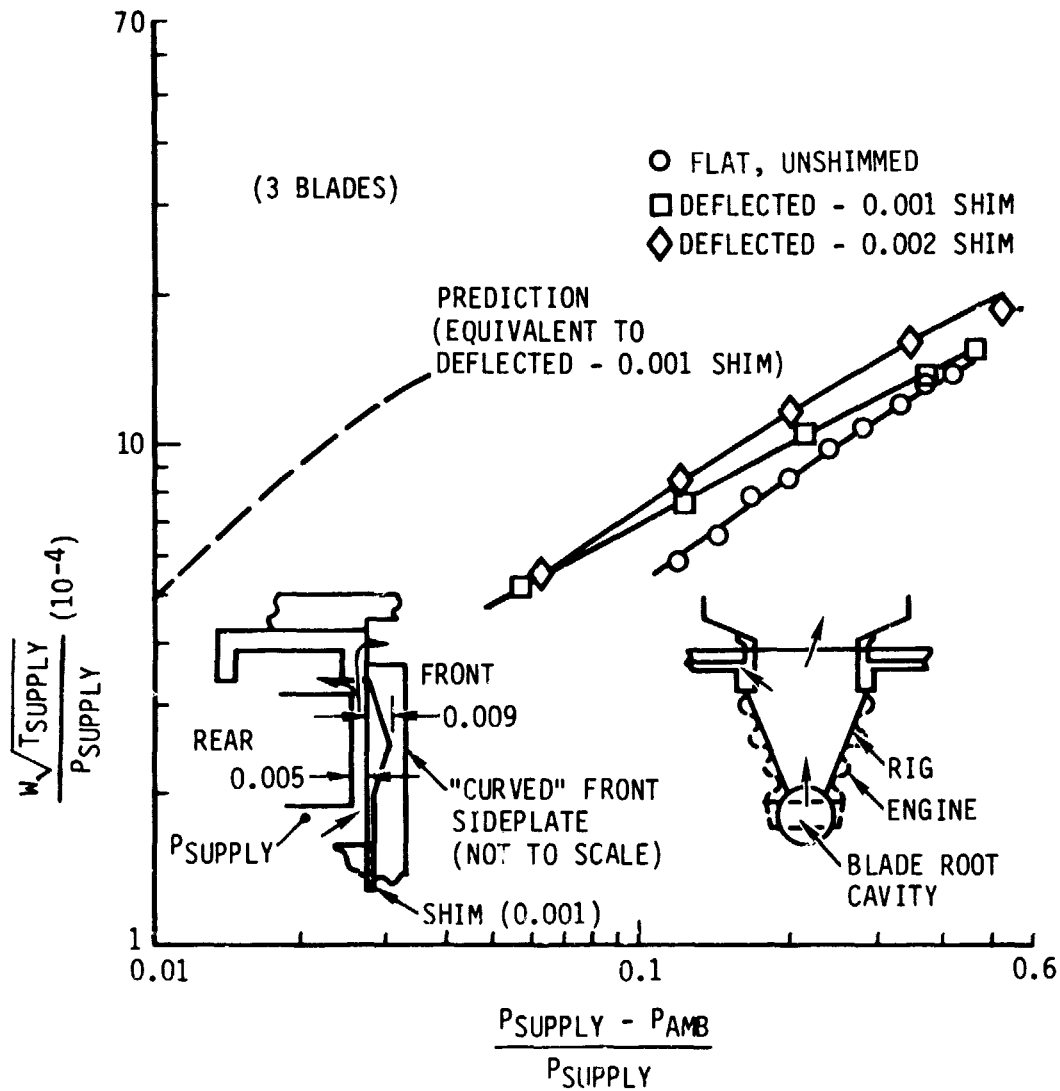


Figure 18 Front Sideplate Test Schematic and Results - Leakage flow was somewhat insensitive to the variations in sideplate configuration, this insensitivity indicates that the trapezoidal slot is the dominant flow area up the side plate. (Dimensions in Inches)

Initially, a flat sideplate was installed to establish the baseline flow area with a .005 inch (five-mil) gap. This installation was followed by a curved sideplate with a one-mil shim at the blade root cavity radius. This configuration simulated the "nominal" sideplate shape and the response to centrifugal and thermal loads that could be expected in an engine environment. A second version of this configuration was evaluated with a two-mil shim to assess the effect of the additional flow area on front sideplate leakage.

As the data show, leakage flow was somewhat insensitive to the variations in sideplate deflection throughout the range of sideplate gaps evaluated. This insensitivity indicates that sideplate leakage flow is relatively small when compared to the flow in the trapezoidal path and suggests that sideplate leakage is not the dominant concern.

Rear Sideplate:

The rear sideplate, unlike the front, has no trapezoidal slots in the disk to provide the primary flowpath area because the rear sideplate is held flush against the disk and blade root attachment, thus permitting no measureable flow. A curved rear sideplate, contoured in a like manner to the front one, did open a very small path; doubling the sideplate clearance to two mils at the supply roughly tripled the flow as shown in Figure 19. This non-linear effect is characteristic of a pipe-flow type leakage path. When the sideplate was then lifted to a uniform .002 inches, the flow did not change appreciably. This lack of response points to the controlling or critical throttling area as being the clearance immediately downstream of the supply cavity and ahead of the maximum bow of the sideplate. Unfortunately, this part of the rig deflection model was not a truly representative simulation, since it did not include non-uniform clearance between the disk and sideplate which could be caused by the bolts passing through the supply cavity in an active engine design. Also, the blade root cavity in the engine is roughly semi-circular, being formed by the bottoms of the fir-tree and its slot. In the rig, a circular hole of the same cross-sectional area was drilled into the "disk" which had the effect of shortening the length of the leakage path in the critical throttling area. These minor inconsistencies might make the direct application of the experimentally determined leakages seem questionable. However, the important point, and the data clearly shows this, is that the measured flows are very low--so low that two additional factors may be more dominant. First, flow paths not modelled in the rig (those created by the twisting of the blade in their slots, or the radii on the fir-tree and slot) may contribute a significant addition to the leakage area. Second, it may be necessary to design flow paths into the disk and/or sideplate to allow sufficient flow for sideplate cooling requirements.

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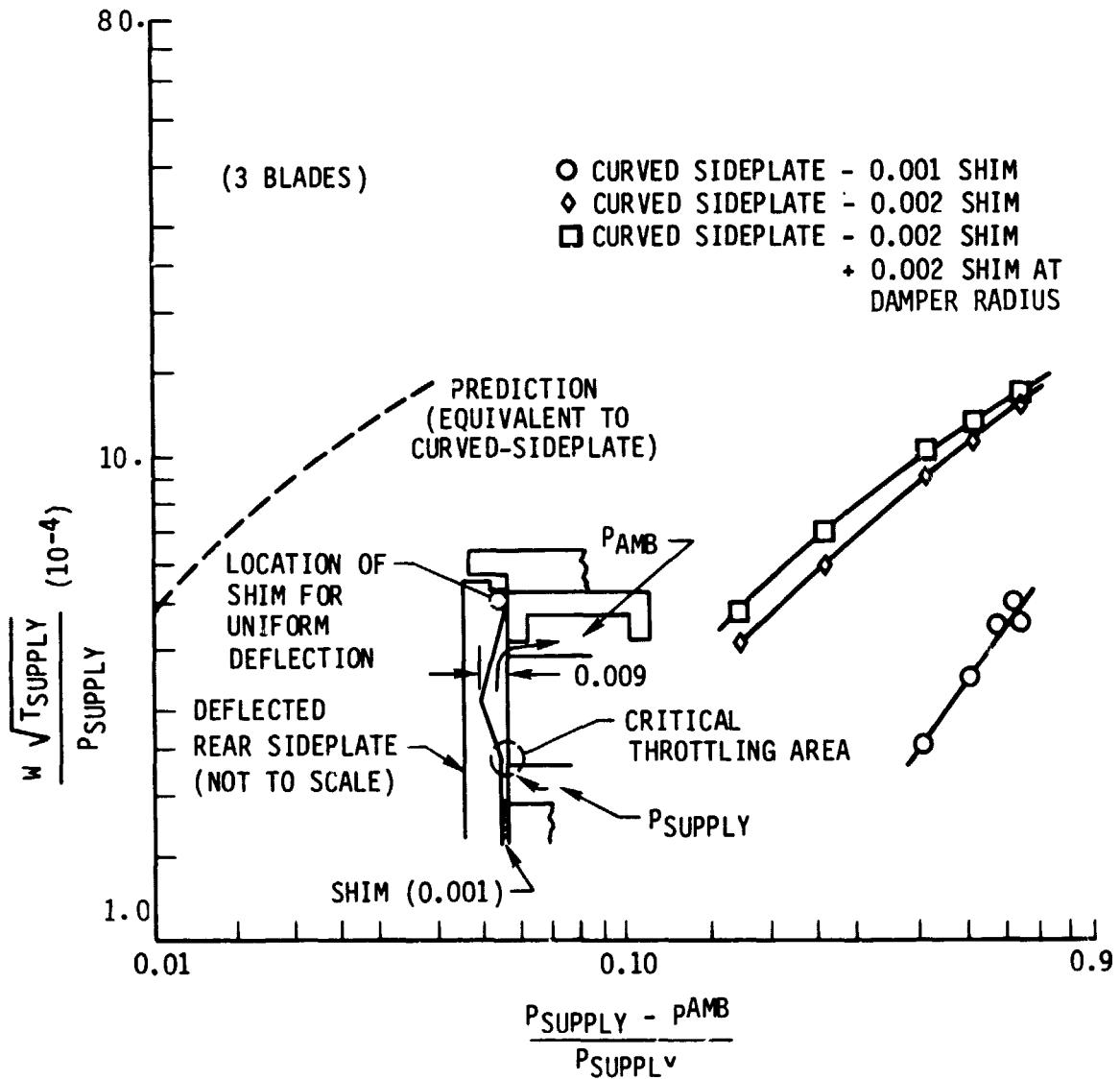


Figure 19 Rear Sideplate Test Schematic and Results - Leakage flows at the rear sideplate are very low. (Dimensions in Inches)

The first of these two factors was not specifically addressed in this program although the results shown in Figure 19 suggest that rear sideplate deflections caused by blade twist might not be the dominant concern. In support of any potential need to provide cooling paths for the component sideplates, a series of tests was performed with a flat rear sideplate, shimmed uniformly off the disk, as in Figure 20, to provide variations in the cooling flow rate. The path is characteristic of Fanno line flow and although the absence of a curve in the sideplate makes the path fundamentally different, flow rates appear to be insensitive to this difference (compare curves A and B, Figure 20).

W-Seal

The W-seal testing was accomplished with the blade platforms precisely aligned with the rear of the disk, and the rear sideplate clamped flat against them. In this configuration, the leak path is flow out the rear of the damper cavity and up the rear sideplate. The dominant restriction in this leakage path is the contact area of the sideplate against the blade platform. The flow escapes this restriction by one of two routes: either past the W-seal, or under the W-seal and into the platform gaps (see detail in Figure 21). As the data show, in figure 21, leakage flow with and without the W-seal is extremely low. This low flow was due to the fact that contact between the sideplate and the rear of the platforms formed such a good seal that adding another seal did not greatly affect the flow. This might suggest that the W-seal provides little or no benefit in controlling leakage. However, it is important to understand how the W-seal was used in the rig as contrasted to more typical applications.

For lower temperature use, W-seals are plated with a soft metal, such as indium or silver, which improves their sealing capabilities by allowing them to conform to "roughness-scale" surface irregularities. However, to be consistent with the high temperature requirements imposed by an engine environment, the seal in the rig was not plated and therefore did not have this capability to conform to surface roughness. If it is assumed that there is no large scale waviness, which flexible W-seal is designed to conform to, then it should not be expected to offer any improvement over just simply bringing the opposing surfaces into direct contact.

In the engine, however, a slight twisting of the blade root attachment in their slots could open up a gap between the rear sideplate and the blade platform. Also, surface irregularities due to manufacturing tolerances could result in random gaps along the circumference at the rear sideplate-blade platform contact point. Under these circumstances, a W-seal would be essential.

It was not felt necessary, in this program, to evaluate the leakage flow past the W-seal because previous P&WA funded studies have adequately assessed the leakage characteristics of this type of sealing device.

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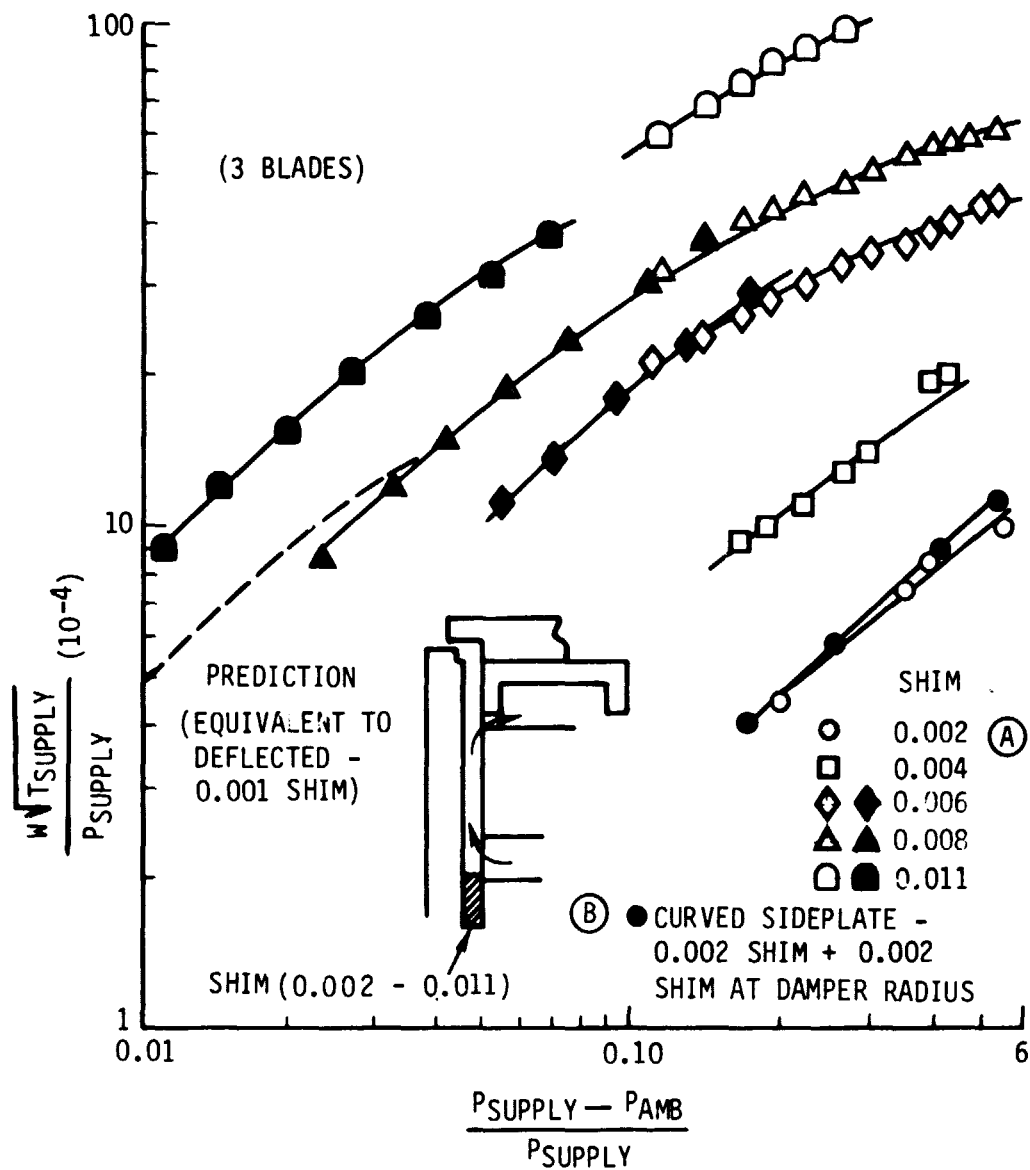


Figure 20 Elevated Rear Sideplate Test Schematic and Results - Fanno line characteristics were evident. (Dimensions in Inches)

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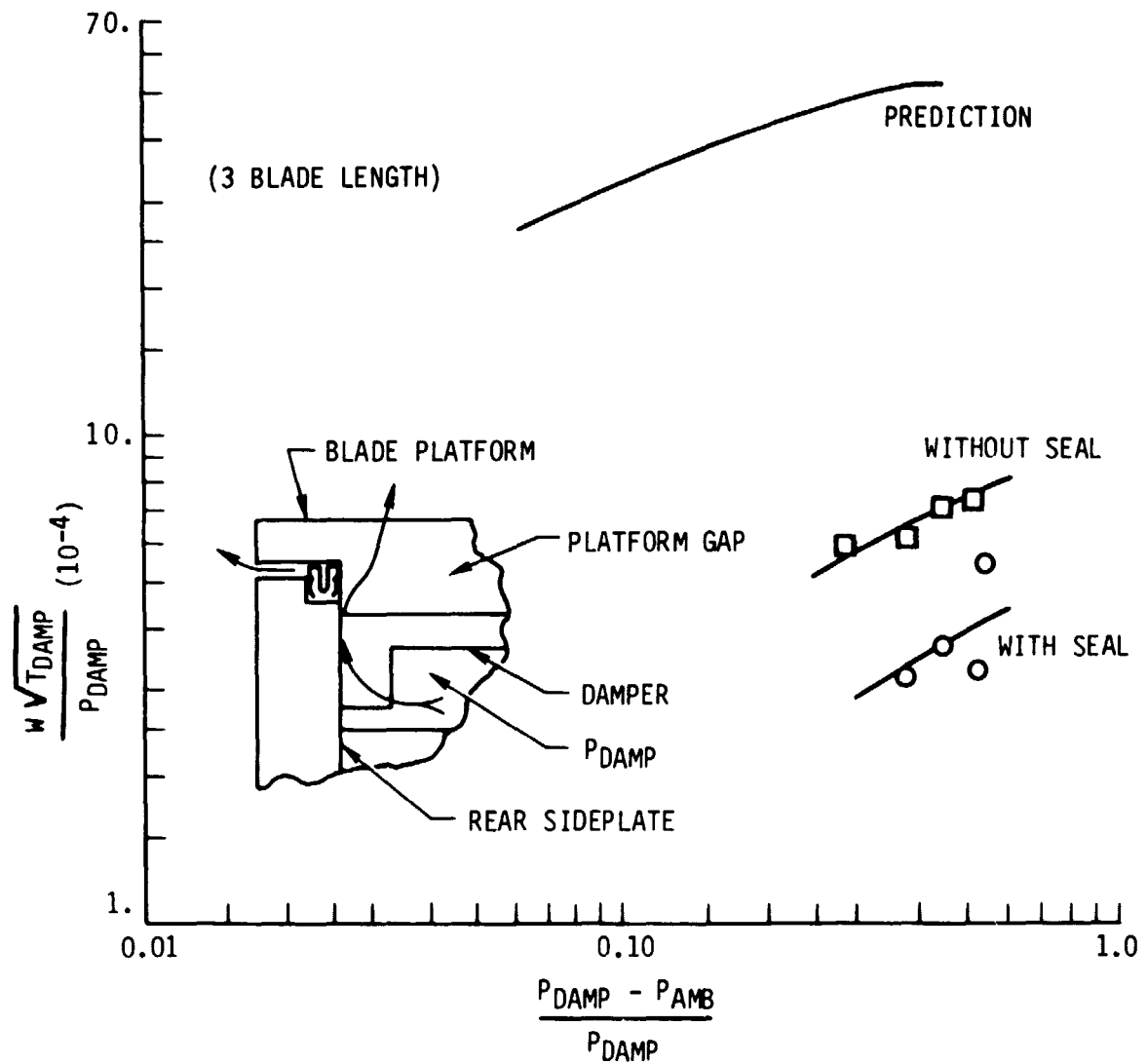


Figure 21 W-Seal Test Schematic and Data - Removing the W-Seal had virtually no effect on the flow.

To summarize all these results then:

1. Flows, in general, were much lower than originally predicted.
2. Deflections of the sideplates due to thermal and centrifugal loads may provide less than the anticipated required areas for coolant flows.
3. The "W-seal" at the outer radius of the sideplate had no effect on the leakage flow with all parts in perfect alignment. Significant leakage reduction will result only if the seal is required to conform to any tolerance related irregularities in blade dimensions or twisting of the blades in the firtree slots.

6.2 Vane Attachment Testing

6.2.1 Feather Seal Optimization

6.2.1.1 Establishing the Baseline Test Configuration

Early definition of the High-Pressure Turbine component vane outer attachment necessitated the use of four feather seal segments as shown in Figure 22(a) primarily because of the S-wall shaped vane platform required for gaspath considerations. In addition, a tapered feather seal slot, Figure 22(c), was selected because it was thought to provide better length-wise sealing due to its inherent self-positioning capability.

Initial testing of the vane outer attachment rig using this feather seal and slot configuration indicated leakage flow levels that were an order of magnitude above the desired level as shown in Figure 23. An analysis of the test rig indicated that there were two primary sources of this high leakage: (1) leakage around feather seal intersections and (2) leakage around the feather seals at the end of the tapered slots due to the additional area caused by the taper (see shaded area, Figure 22(c)). The taper also acted to elevate the seal off the flat slot surface, and increased the effective leakage area at the feather seal intersections.

The problem of feather seal intersection leakage was resolved by redesigning the vane outer platform (essentially adding thickness) so that the four-piece feather seal could be replaced by a two-piece seal, thus reducing the number of intersections from three to one as shown in Figure 22(b). The problem of endwall leakage in the tapered slots was resolved by redesigning the slots to more conventional, tighter fitting straight-sided slots as shown in Figure 22(d).

Once these configuration changes were accomplished, leakage flow levels proved to be in the range desired and testing could proceed.

6.2.1.2 Comparison of Test Results

The various feather seal configurations tested are as shown previously in Figure 3. Test results are organized to isolate the effects of the changes noted. As mentioned in Section 5.3.2.2, leakage paths at the ends of the feather seals were selectively plugged so that the true leakage along the length of the feather seal could be assessed as well as the effects of endwall leakage.

Case 1: Two-Piece Feather Seal with Overlap - Evaluate the effect of feather seal thickness and plugging end leaks.

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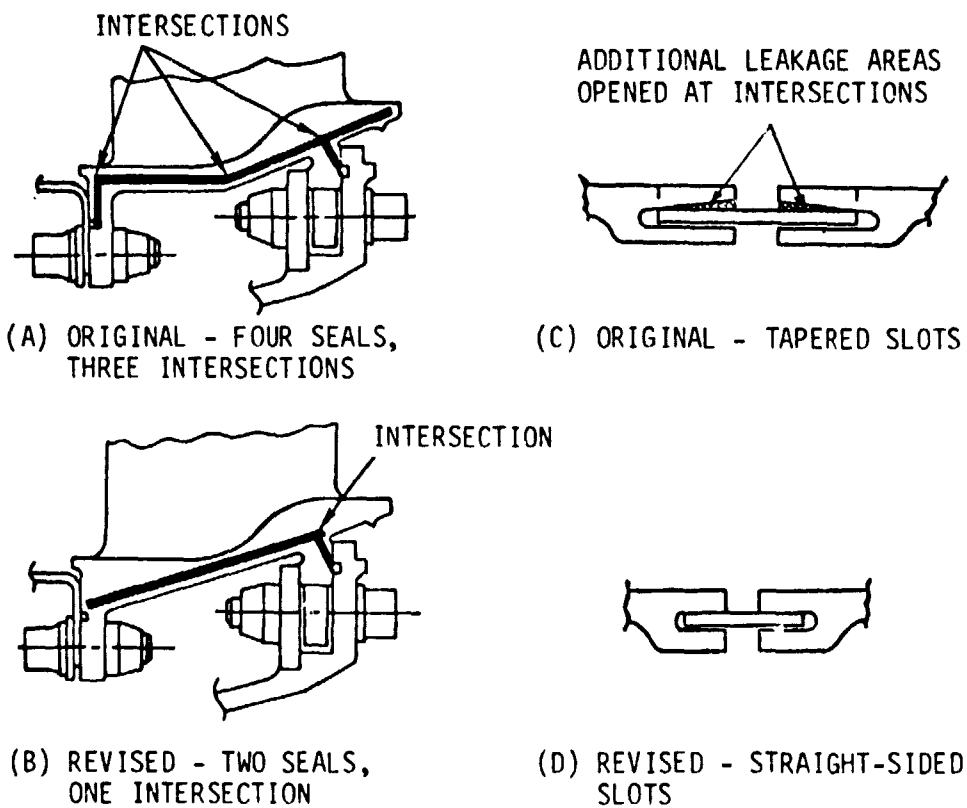


Figure 22 Feather Seal Configuration, Original and Revised - The revised configuration provided a more realistic reference point for further leakage testing.

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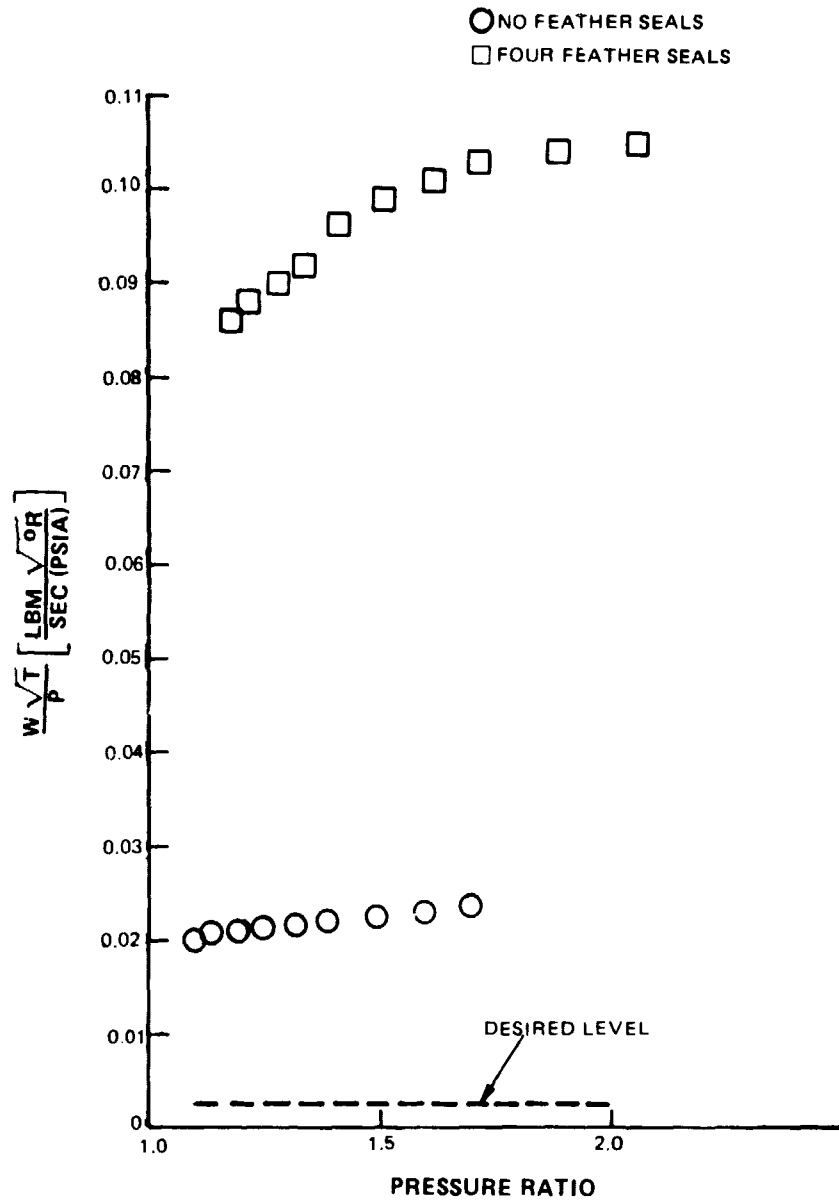


Figure 23 Four Feather Seal Vane Outer Attachment Rig Exhibited Leakage which was an Order of Magnitude Above the Desired Value

For this test, feather seal slots .2 in. wide and .025 in. thick were fabricated using an electrodischarge machining (EDM) process. Results of the test are shown in Figure 24 and indicate that the predominant factor is leakage at the ends of the feather seals. This leakage appears to mask any effects due to feather seal thickness in the "no plug" and "front plug" cases. At first glance, the case where both ends are plugged seems to indicate the real effect of thickness. However, such a determination might be questionable at the low flow rates shown because the differences may be within the range of test accuracy at those levels.

Case 2: Two-piece feather seal with overlap - evaluate the effect of slot fabrication methods and plugging end leaks.

The EDM process was thought to generate a certain amount of "waviness" along the length of the feather seal slot which could create new leak paths. Grinding the slots to the same dimensions was a way of removing potential waviness and thereby creating a better sealing surface. Test results shown in Figure 25 bear out this contention. Again, the effect of end leaks is dominant and almost completely masks the benefit derived from the ground slot for the "no plug" case, although this should be qualified to some degree by the accuracy of the test data at low flow rates. Since the ground slot showed a definite advantage, all further test results are based on test configurations utilizing ground slots.

Case 3: Two-piece feather seal with overlap - evaluate the effect of removing overlap and plugging end leaks

Allowing slots to overlap (one extending past the other in a "T" intersection, as shown in Figure 26) creates an undesirable leak path. Figure 27 indicates that eliminating this overlap can result in a significant leakage reduction. It was not expected that plugging would have a significant effect on this particular leak path, however, the data seem to imply otherwise (i.e., note the difference between "overlapped" and "non-overlapped" lines with and without the front plug). A partial explanation for this inconsistency is that when the front plug was removed and overlap eliminated, the long feather seal shifted forward partially closing the end gap that had previously been filled by the plug. This caused the non-overlapped configuration to behave somewhat like a "front plug" configuration. In addition, the forward end gap is more sensitive to seal rotation than the rear gap and this could have also contributed to the seemingly inconsistent differences noted.

Case 4: Two-piece feather seal without overlap - evaluate the effect of feather seal thickness and plugging end leaks in a ground slot.

As discussed in Case 1, feather seal thickness did not seem to have an appreciable effect on leakage. However, it was possible that thickness effects in that case may have been overshadowed by the effects of waviness in the EDM slot. If this were the case, then perhaps the

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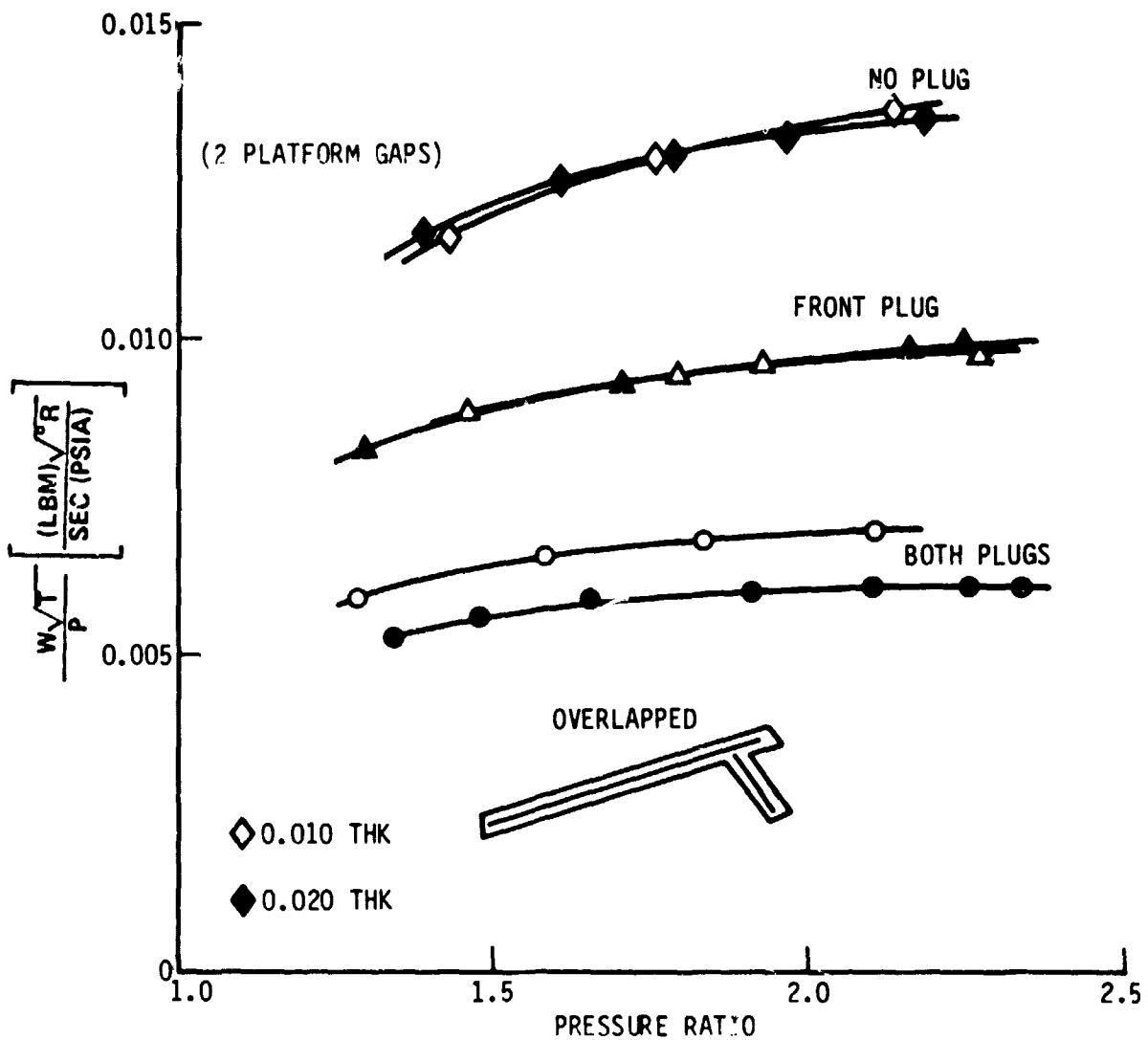


Figure 24 Comparison of 0.010- to 0.020-Inch-Thick Two-Piece Overlapping Feather Seals in EDM Slot - The predominant factor is leakage at the ends of the feather seals.

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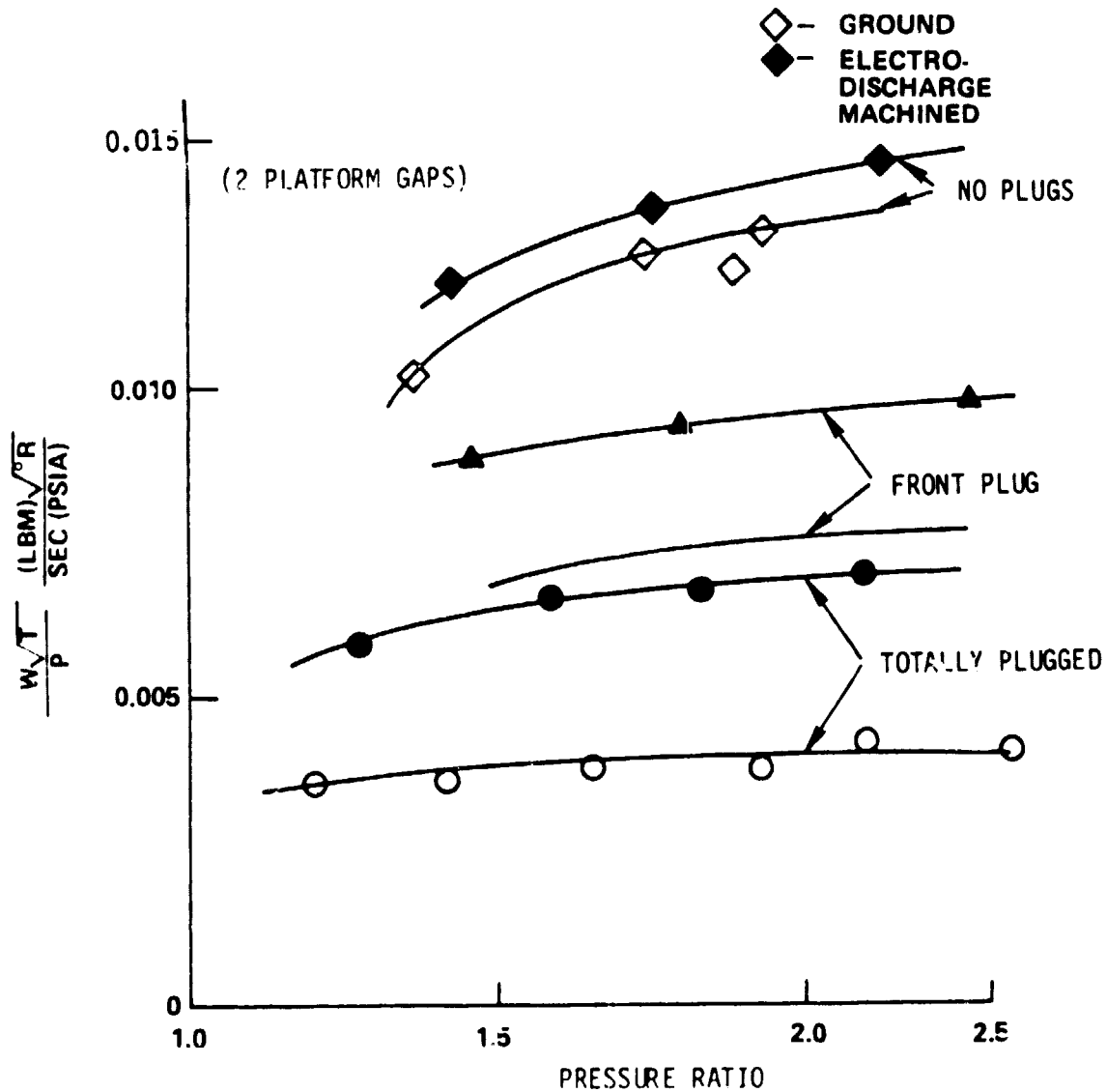


Figure 25 Two-piece overlapped Seals in Ground Versus Electrodischarge Machined Slots - The EDM process generated a certain amount of "waviness" along the length of the feather seal slot which could create new leak paths; grinding the slots removed this waviness and thereby created a better sealing surface.

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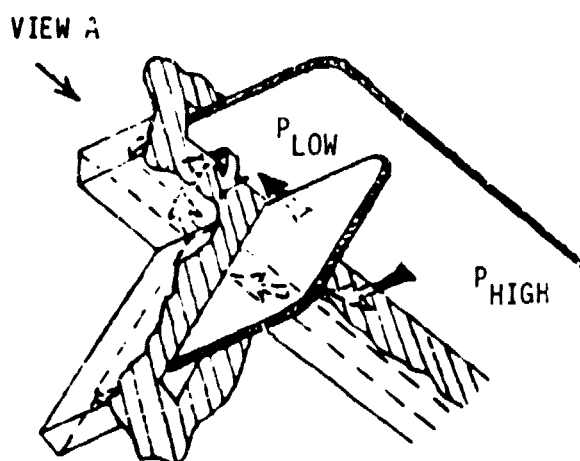


Figure 26 Overlapped Feather Seal Leakage Paths - The presence of the overlap at the intersection will always open some leak path under even the best conditions.

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GROUND O.D. F. S. SLOT - 0.010" THK

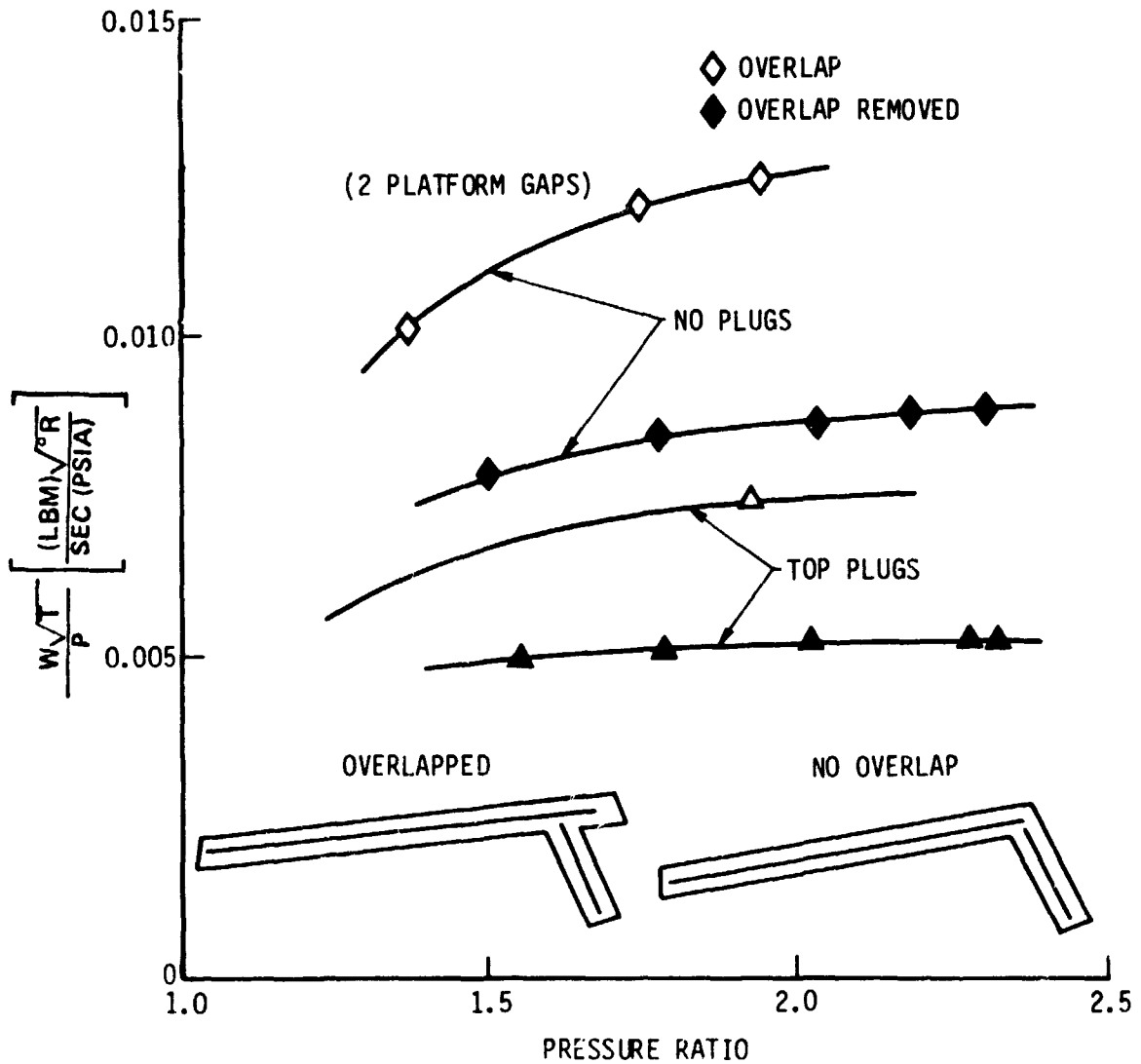


Figure 27 Comparison of Overlapped Versus Non-Overlapped Feather Seal - Eliminating the overlap can result in a significant leakage reduction.

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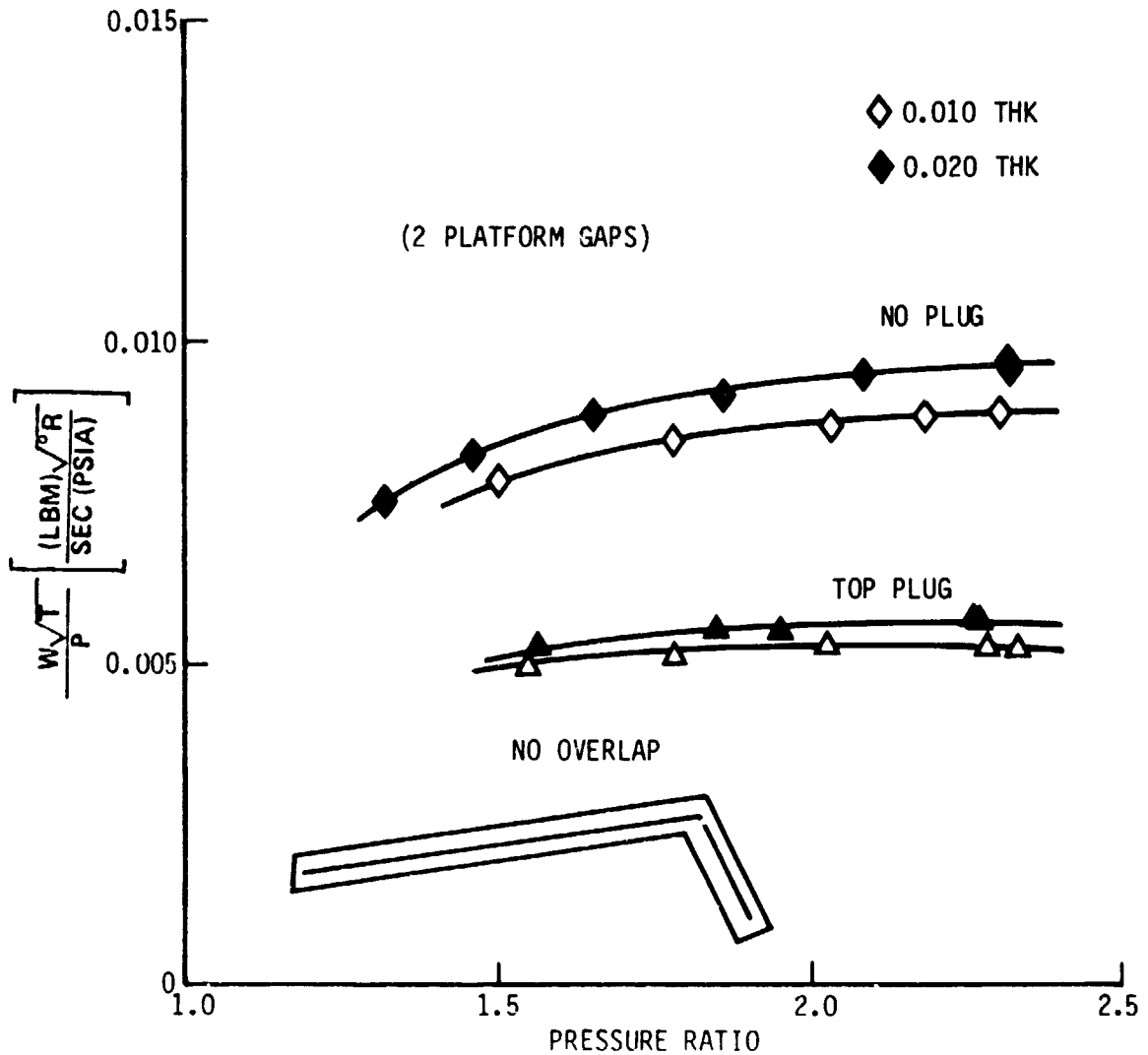


Figure 28 Comparison of 0.010- Versus 0.020-Inch-Thick Feather Seals Using a Ground Slot and a Two-Piece Non-Overlapping Seal - The effects of thickness were more noticeable in the ground slot, however, feather seal thickness is not the dominant factor.

effects of thickness might be more noticeable in the ground slot. Test results shown in Figure 28 indicate the validity of this presumption, but also confirm that feather seal thickness is not the dominant factor (at least in the range of practical thicknesses).

Case 5: Comparison of two-piece feather seal without overlap to two-piece feather seal with crook and single piece curved feather seal - all with and without front plug.

The two-piece feather seal has one intersection that is a potential leak path. It was thought that this path could be eliminated by using a single-piece feather seal or at least reduced by modifying the "contact" end of the short feather seal to resemble a sheet-metal seal. Figure 29 indicates that neither of these modifications yielded any benefit; probably due to the fact that (1) leakage through this intersection is small relative to total leakage and (2) the modifications may not have been as adaptable to rig motions as the simple two-piece feather seal.

Case 6: Comparison between totally plugged two-piece feather without overlap and two-piece "long" feather seal without overlap.

In a real engine environment, it may be impractical or impossible to consider the plugging of platform gaps as a way of eliminating feather seal end gaps. A means of producing the same effect is to extend the feather seals to the front and rear of the platform and seal the ends with a mount flange. The two configurations thus become similar and comparable results would be expected in the evaluation of their leakage characteristics. This similarity was verified by the results shown in Figure 30, which also indicates the extremely low leakage flow rates for these configurations. To achieve these low rates required some hand-fitting of the feather seals in the individual slots - perhaps not the most practical assembly procedure.

6.2.1.3 Platform Displacement Effects on Feather Seal Leakage

Relative motion between vane platforms due to aerodynamic and thermal loads on the engine hardware can cause the feather seals to shift (or rotate) in their slots. This rotation results in the creation of leakage paths through the platform gaps; identified as A_2 and A_2' in Figure 31. Although the rig was designed to simulate the twist, rock, and tilt motions that could cause these feather seal shifts, a means of quantifying the rig motion was never developed due, in part, to the space limitations imposed on the rig. The platforms were free to rotate about axes parallel to the engine axis -- "rock". This displacement tends to shear the feather seals, with excessive amounts deforming the seal into a slight "S" across its width as shown in Figure 32. Although no data were recorded during these particular displacement tests, visual observations of the static pressure gages indicated that the sealing properties of the deformed seals remained intact after the shearing force was removed. Tilting of the vanes (rotating fore-and-aft) was also possible, but had a minor and seemingly random, non-repeatable impact on the leak level.

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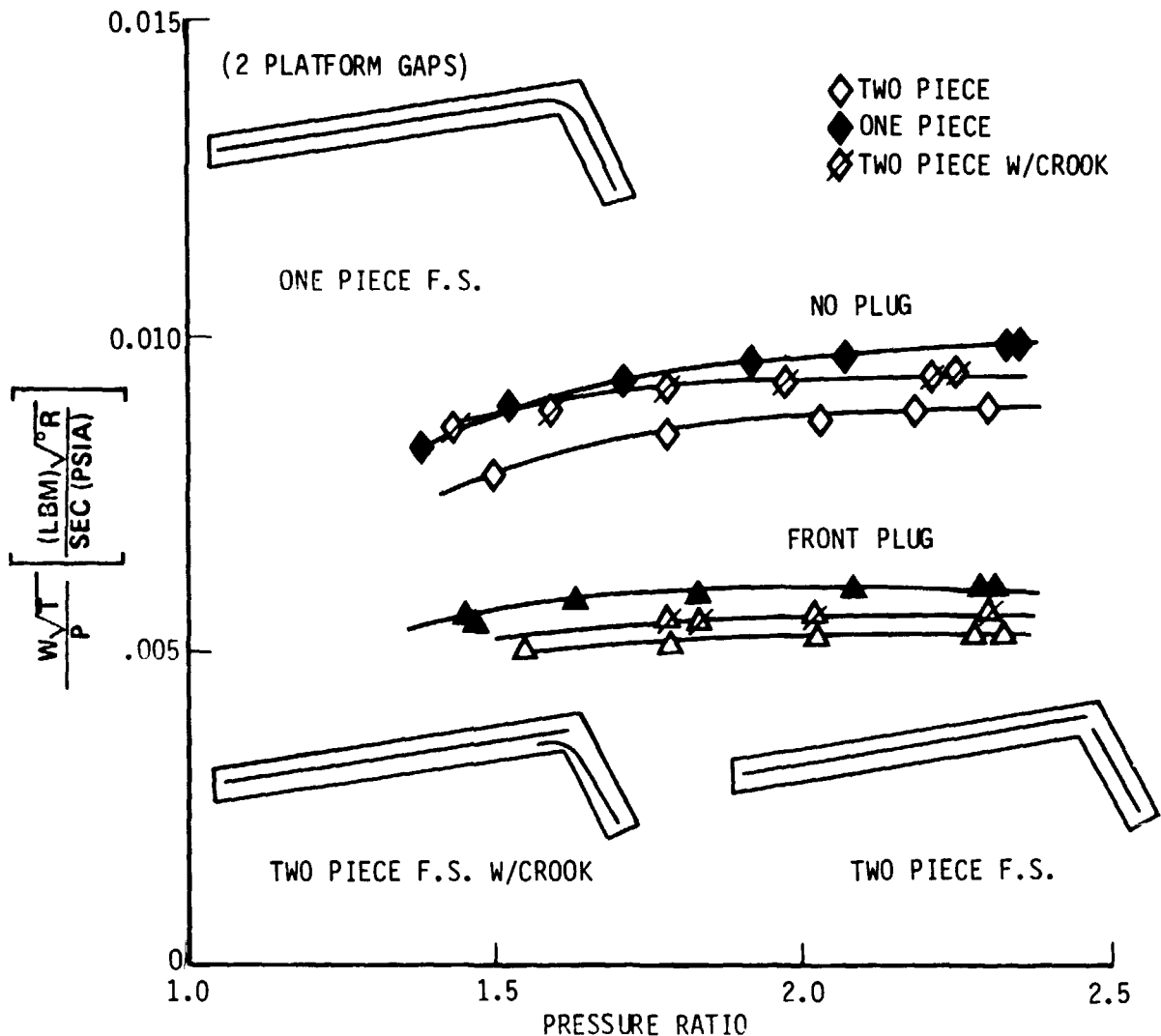


Figure 29 Comparison of One-Piece, Two-Piece, and Two-Piece-With-Crook Feather Seals Using a Ground Slot and 0.010-Inch-Thick Non-Overlapping Seals - Modifications to two-piece feather seal yielded no benefit due to the fact that (1) leakage through this intersection is small relative to total leakage and (2) the modifications may not have been as adaptable to rig motions as the sample two-piece feather seal.

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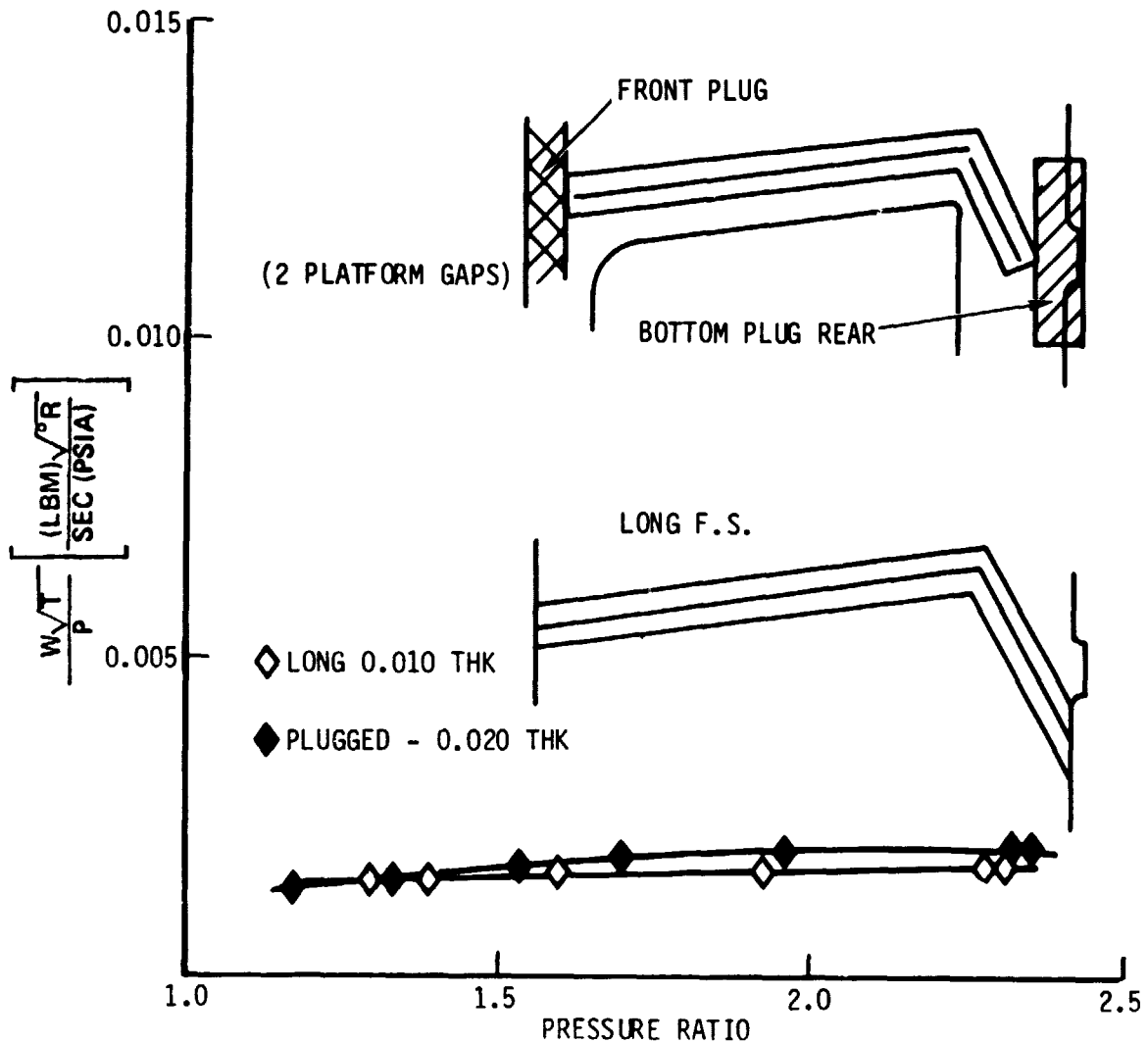


Figure 30 A Comparison of 0.010-Inch-Thick (Long) Versus 0.020-Inch-Thick (Plugged) Two-Piece Feather Seals Using a Ground Slot - The similarity of the two configurations is verified by the results which also indicate their extremely low leakage flow rates.

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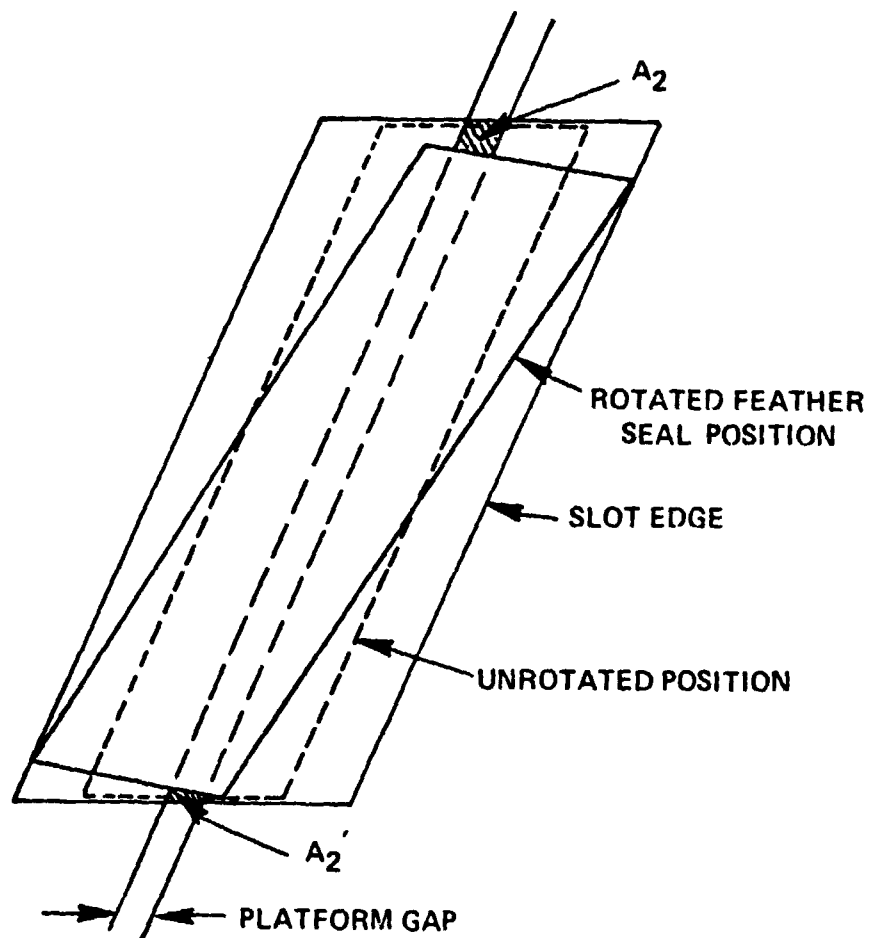


Figure 31 Areas Opened by Feather Seal Rotation - Seal rotation results in the creation of leakage paths through the platform gaps; identified as A_2 and A_2' .

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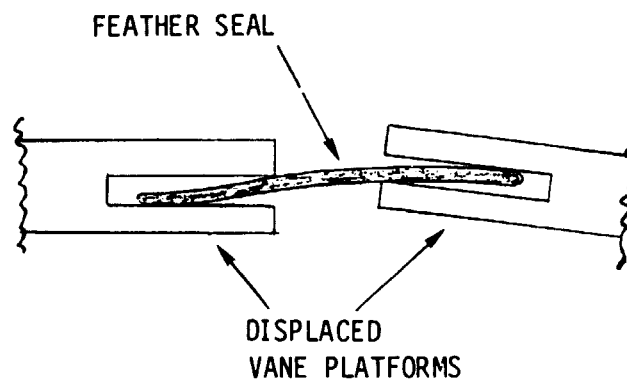


Figure 32 Rock-Induced Feather Seal Deformation - The sealing properties of the deformed seals remained intact after the shearing force was removed.

The rotation problem can be considered as equivalent to a feather seal which is shorter than its slot, since it opens the same kind of leak. This fact led to the consideration of slot overlap and feather seal crooks. Under ideal circumstances, both are undesirable and unnecessary because the presence of the overlap at the intersection will always open some leak path under even the best conditions. These leakage paths were illustrated in Figure 26.

It might appear that in practice, the overlap would prevent the main feather seal from opening an intersection leak if it slides or rotates forward. It turns out, though, that this effect is significant only if the feather seal is too small for its slot to begin with; otherwise, the overlap leak is larger than the intersection leak it eliminates. Quantifying this overlap leak is difficult because the flowpath is complicated and is highly dependent on the position of the rear feather seal relative to the main one. For instance, if the two do not make contact, air can exit along the full width of the slot. Ensuring contact between the seals to cut down this area could be accomplished by a crook on the rear feather seal. In addition, if the slot overlap is eliminated, a task which fabrication tolerances might make impossible - the crook can still be beneficial by covering the type of intersection leak opened when the front seal shifts forward.

On the other hand, a crook in the feather seal will require a local relief in the slot to accommodate the double seal thickness. Also of concern is the bend itself and whether forming it will introduce waviness in the seal which could compromise its seating capabilities.

These problems might lead to the conclusion that a one-piece bent feather seal would eliminate the intersection leak and therefore represent the most desirable configuration. As was shown in Figure 29, either this did not happen in the tests or the desired effect was countered by increased leakage elsewhere, due to seal displacement and possibly poor seating.

In an attempt to quantify seal displacement effects due to vane "rock", a test case was evaluated using a two-piece feather seal with and without end plugs. The results of this effort are shown in Figure 33. In the "no-plug" case, the seal has maximum freedom to rotate and therefore showed the greatest additional leakage flow. The case with both plugs is equivalent to a situation where the fit of the seal in the gap is so tight that seal rotation is impossible (or extremely limited). However, in a real design, some tolerance is necessary for the following reasons: when the vane is "rocked", the short feather seal, being at a right angle to the long feather seal, is compressed along its length in a tight-fitting slot. Similarly, if the vane is twisted, this same type of compression is imposed on the long feather seal, while now the short feather seal is sheared. To avoid this lengthwise compression, which could "unseat" the seal, enough end play must be allowed to avoid interference between the ends of the feather seals and the slots. For the long feather seal, this end play is what permits feather seal rotation. The short feather seal, due to its slot geometry, does not open an end gap when rotated and therefore is more readily shortened.

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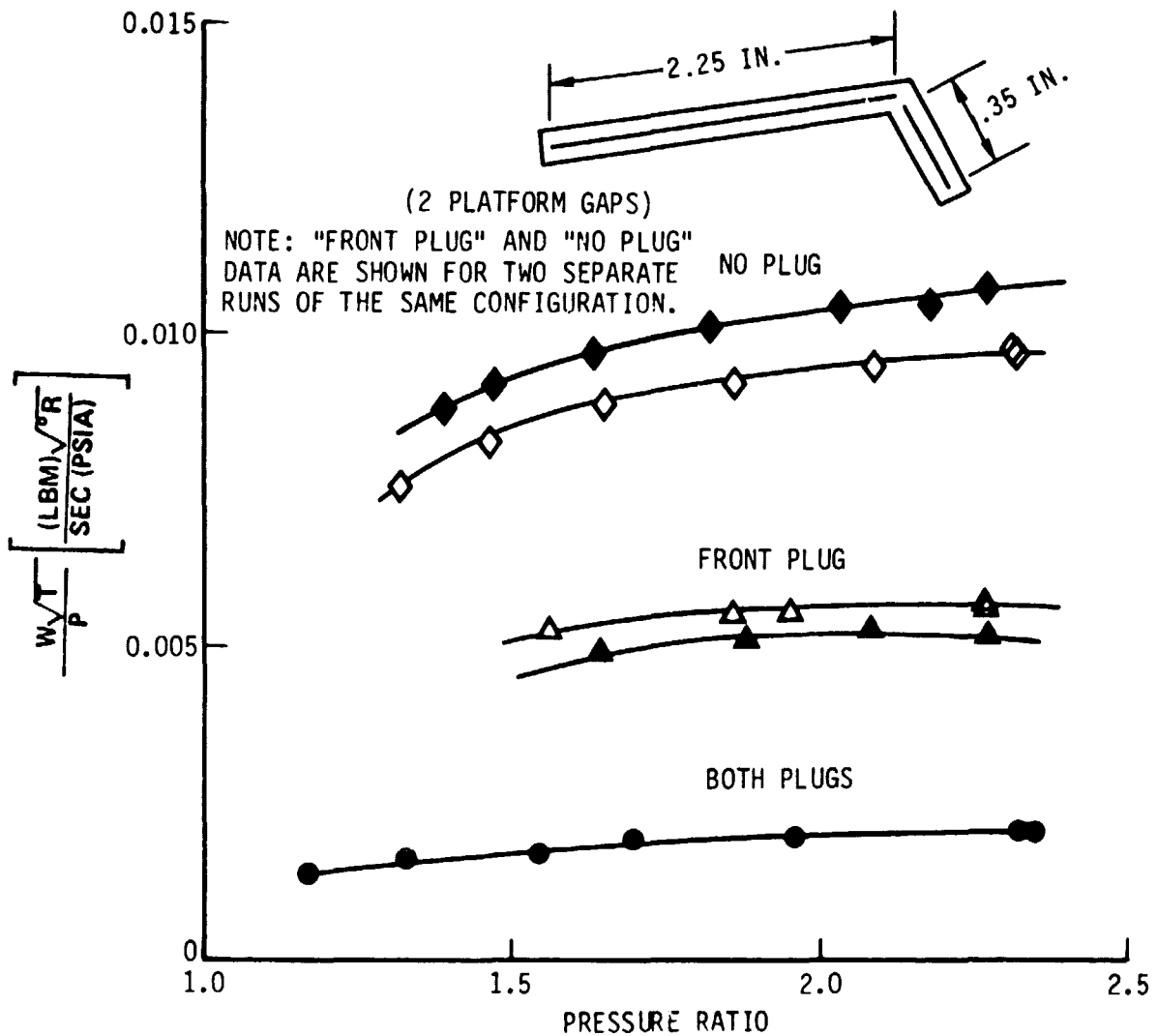


Figure 33 A View of Two-Piece, 0.020-Inch-Thick Feather Seal Performance Using Ground Feather Seal Slots - In the "no-plug" case, the seal has maximum freedom to rotate and therefore showed the greatest additional leakage flow.

Shortening the rear feather seal too much will open up undesirable intersection and end gap leaks, especially since the short feather seal has a higher pressure ratio across it because of its location at the rear of the vane platform.

Referring again to Figure 33, the lack of repeatability of test results for the "front plug" and "no plug" cases was attributed to inadvertent seal displacement in one of the two runs. The real effects of seal rotation are probably best represented by the level of leakage shown in the "front plug" case. The case where both ends of the feather seal slot were plugged is not considered representative because the seal/slot fit is too tight and would probably lead to bind-up in an engine environment, with a consequent opening of leak paths caused by that phenomenon. The data do suggest, however, that leakage is minimized when seal length and slot width dimensions are closely controlled to limit seal rotation and end-play.

A similar series of tests was run to simulate the effect of vane platform "tilt" on feather seal displacement and subsequent leakage. The results of these tests are shown in Figure 34 and indicate that variations in tilt equate to a nominal 0.002 increase in flow parameter. The highest flow occurred when the platforms were tilted to the extent of binding the seals (i.e., a platform to platform step of about twenty mils for a ten mil feather seal). Single piece feather seals showed a somewhat greater sensitivity to tilt; this effect may be due to the fact that the two segments are not free to move independently and therefore cannot conform as well to misalignments.

6.2.1.4 Calculation of Effective Leakage Areas

The goal of the feather seal evaluations was to achieve a configuration which would reduce leakage to an equivalent one mil per inch of feather seal length (effective gap). In addition, sensitivity factors were needed to indicate the relative contributions to total potential leakage caused by the test variables evaluated. In order to do this, it was necessary to convert flow parameter data into effective gaps. The rig geometry used to calculate effective gaps is shown in Figure 35 and Table 5.

The approach used was to examine the flow differences in the choked regions (pressure ratio of about two) of the various data plots (Figures 24 through 30). These choked flows are simply proportional to effective area if an orifice-type leak path is assumed. The calculations of effective flow area and effective gap are straight-forward and utilize the simple empirical relationships:

$$\text{Effective Area} = 0.941 \times \text{choked flow parameter, (in.}^2\text{)}$$

$$\text{Effective Gap} = \frac{\text{Effective Area}}{L_f} \text{ in.}$$

where:

- o L_f = feather seal length (inches)
- o Flow parameter is read directly from the data plots

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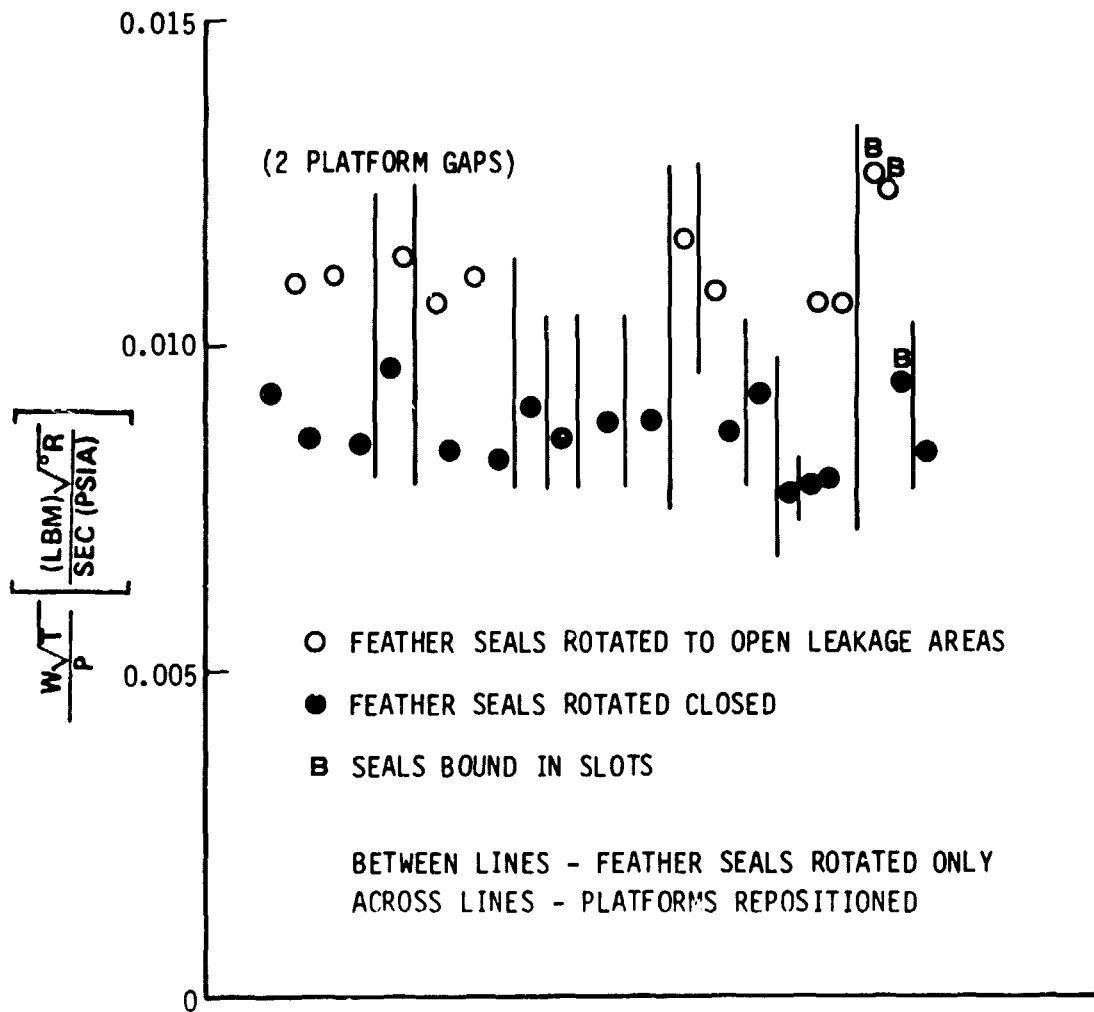


Figure 34 Two-Piece 0.010-Inch-Thick Feather Seal Performance Using Ground Slots - Variations in tilt equate to a nominal 0.002 increase in flow parameter.

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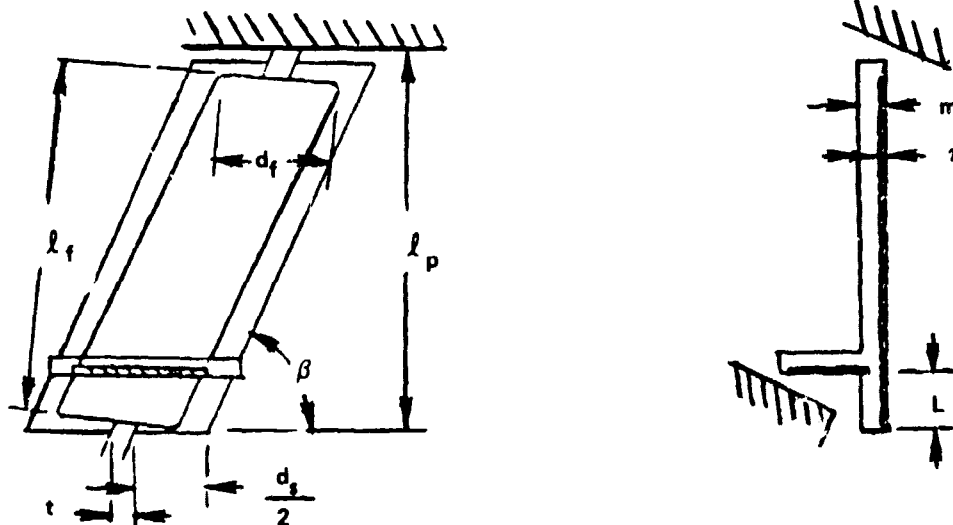


Figure 35 Vane Rig Geometry - The rig geometry used to calculate effective gaps is shown.

TABLE 5

GEOMETRY USED TO CALCULATE EFFECTIVE LEAKAGE AREAS

	Rig
β (deg.)	52
t (in.)	.063
d_f	.453
<hr/>	
d_g	.52
L	.04
m	.025
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r	.010
l_f	1.81
l_p	1.87

The resulting effective gaps and effective flow areas are summarized in Table 6 for the base case and the leakage variables tested. The base case is represented by the ground slot long feather seal configuration whose flow parameter-pressure ratio relationship is shown in Figure 30.

TABLE 6

SUMMARY OF EFFECTIVE GAPS AND FLOW AREAS

Variable	Flow Area (Rig-Measured)	Flow Area (Calculated)	Effective Gap ~ mils
Base Case	0.0017(1)	---	0.6
Front Feather Seal End Leak	0.0033-0.0038	0.0037(2)	---
Rear Feather Seal End Leak	0.0026-0.0034	0.0032(2)	---
Effect of Overlap	0.0022	0.0022(2)	---
Effect of EDM Slot	0.0020	---	0.7
Effect of Seal Rotation	0.0022-0.0026	0.0025(2)	---

Notes: (1) Includes residual end leaks and intersection leaks
(2) assumes a discharge coefficient (C_d) = 0.85

In the table, effective gaps were not calculated for end leaks, rotation effects, or overlaps because the flow areas for these are more representative of holes than linear slots. In these cases, flow area is a better measure for comparison. Similarly, flow areas were not calculated for the base case and the EDM slot because the experimental values were felt to be more realistic. A range of measured flow areas is shown for those cases where more than one set of data was available. The sensitivity factors shown are to be considered as individual effects and should not necessarily be considered as additive. They do substantiate the need for controlling external leak paths.

To summarize these results:

- (1) There were no significant differences in minimum leakage between ten and twenty mil feather seals, although for a given slot width, a ten mil feather seal permits greater relative "tilt" motion between platforms.
- (2) Slots formed by grinding leaked significantly less than those formed by EDM. This was for the feather seal proper and did not include end leaks. Therefore grinding would be the preferred method, particularly if the slots are straight and can be extended to the endwall. Both methods may require some development before they can meet production standards.
- (3) Allowing seals to overlap - one extending past the other in a "T" intersection - opens a leak path. Therefore, overlap should be avoided if at all possible.
- (4) Modifying a two-piece feather seal configuration by putting either a crook in one seal to cover the intersection, or replacing the two seals with a single curved seal, had no significant impact on leakage.
- (5) A closely controlled seal length and a slot geometry which minimizes seal rotation are required to minimize end leaks and intersection leaks.
- (6) By close attention to the above-mentioned factors, it is possible to achieve a feather seal effective gap equal to or less than one mil per inch.
- (7) Two-piece feather seal had the lowest leakage.

6.2.2 Attachment Leakage

Testing of the front inner diameter attachment was never attempted since it represented a flange-type leak and the rig parts were not designed to model such a leak. The front outer diameter attachment was tested with limited success using a crude wire rope which exhibited many problems (see discussion in Section 6.2.3). The rear outer diameter attachment exhibited no measurable leakage even without the wire rope in place. This fact was not surprising considering the smooth surface, tight clamp and "hook" formed by the attachment clamp.

6.2.3 Wire Rope

Wire ropes have been the subject of numerous studies over the years for use in various engines. While they were sometimes used as caulking to plug large gaps, they have come to be idealized as a high-temperature O-ring: flexible, resilient, and tightly sealing. The supposed ability of wire rope to conform to large thermal motions was a factor in applying it to the EEE turbine in the first place. In fact, the major concern about wire rope is that it will exhibit large deformation hysteresis which will prevent continuous sealing contact under inevitable thermal motions.

Studies were conducted to evaluate wire rope in an environment typical of the EEE turbine; particularly as a means for sealing end gaps associated with vane attachment feather seals.

Typically, wire rope consists of a flexible fibrous core enclosed in a metal braid. The core can be asbestos, a refractory material, such as Fiberfax, or a high temperature alloy such as is used in the external braid.

These three types are discussed in the following sections.

6.2.3.1 Asbestos Core

Asbestos was initially the favored core material and is still used in certain applications. However, room temperature experiments with asbestos-cored ropes exhibited a pronounced lack of resilience once the rope was compressed. In addition, asbestos decomposes into a powder within a temperature range of 1000°F to 1500°F. Since the areas where wire rope might be applicable in the EEE turbine could reach a temperature as high as 1400°F, the use of asbestos cores would not be feasible.

6.2.3.2 Refractory Material Core

Most refractory materials have a capability to withstand temperatures in the 2000°F range. This capability would be more than adequate for EEE turbine applications. Also, mechanical properties of this material are superior to asbestos. However, durability of refractories is still questionable and would require further analysis. This analysis was outside the scope of the present program so refractory cored wire ropes were not evaluated.

6.2.3.3 Metal Cores

Two types of metal-cored ropes were evaluated: one was composed of fibers on the order of five mils, the other of fibers an order of magnitude less (about .5 mils). The first was fairly stiff and had the same outward appearance as asbestos-cored rope; the latter, composed of fibers similar to those in Feltmetal, was soft and resilient, looking a bit like knitting yarn. Based on a qualitative evaluation of the different materials, a hybrid rope composed of a foil braid was selected (for flexibility and low porosity). It was not possible to find a vendor interested in making such an item, therefore braided hollow tubes without cores had to be used instead. These "hollow tube" wire ropes had a hard, coarse surface and were notably lacking in resilience, as room temperature experiments showed.

Leakage tests of the all-metal ropes showed a strong relationship between sealing ability and how far the rope was compressed, with the minimum effective gap measured at about 1.5 mils. However, once compressed, the rope remained permanently deformed and lost its sealing capability when compression was released.

To summarize:

Wire rope, in its present state of development, is not a feasible sealing concept for EEE turbine applications. However, the "hybrid" concept is promising and should be considered for further development.

6.3 Blade Outer Airseal

Once wire rope was eliminated as a potential leakage control concept in the outer air seal package, the objective of testing centered on the evaluation of leakage (1) around the feather seals between outer air seal gaps and (2) through the "w" seals at the ends of the platforms. The rig model consisted of a tapered EDM slot with a 0.020-inch-thick feather seal as shown in Figure 36. The gap shown was adjustable and could be closed completely.

6.3.1 Evaluation of Feather Seal Leakage

The approach used here was to first assess the total leakage through the outer airseal gap as a function of gap width without the feather seal installed; then install the feather seal and reassess the leakage. Results are shown in Figure 37 and 38.

Figure 37 indicates the expected variation in flow parameter with increasing gap size. The fact that there was some measurable leakage, even with the gap closed, is an indication of the residual leakage in the rig (i.e., end leaks, leakage through the gap due to tolerances, through the "w" seal, and other miscellaneous leak paths peculiar to the rig.)

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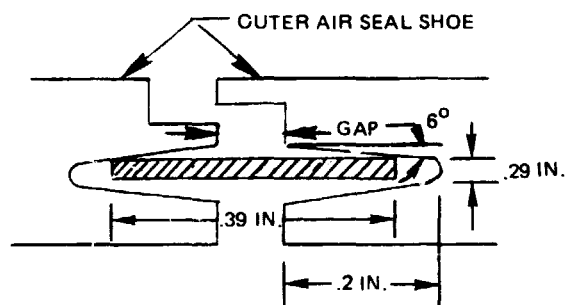


Figure 36 Tapered EDM Slot with a 0.020-Inch-Thick Feather Seal - The gap was adjustable and could be closed completely.

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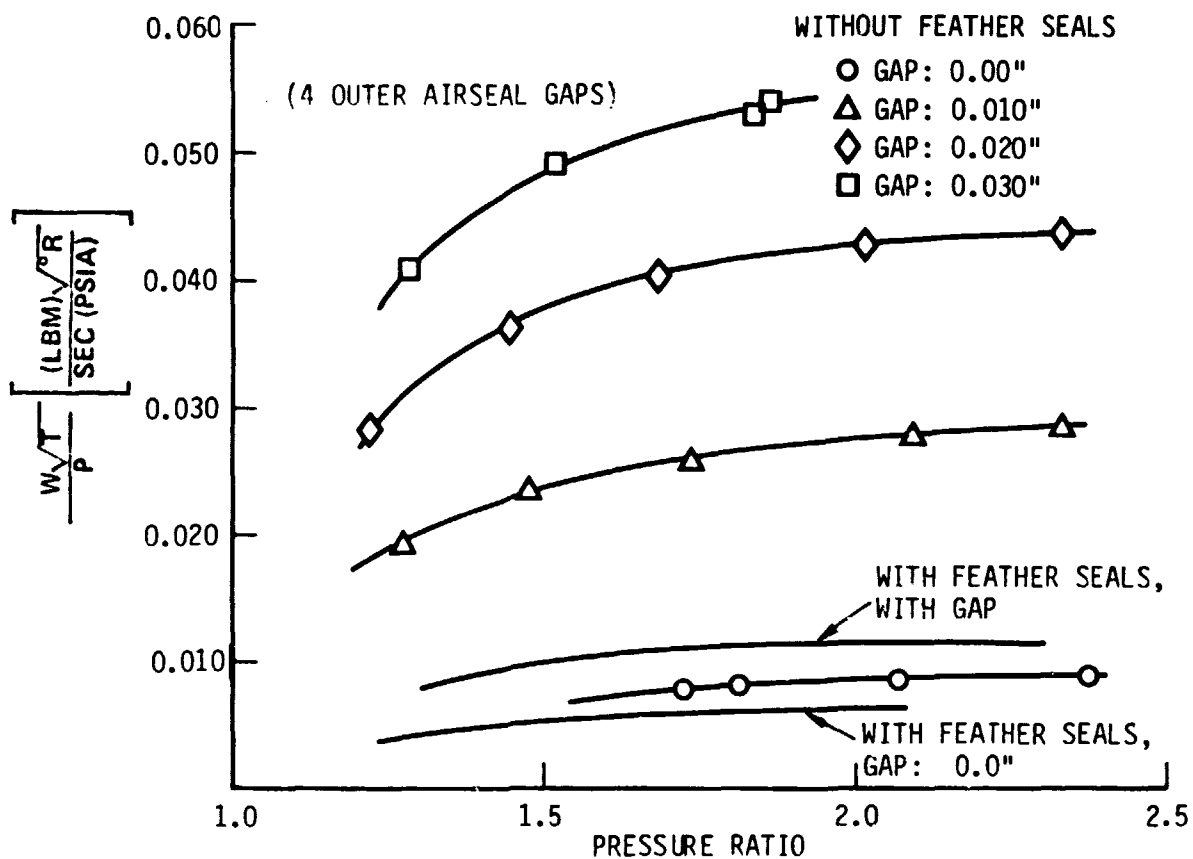


Figure 37 A Comparison of Outer Air Seal Leakage With and Without Feather Seals - Feather seals were judged successful in reducing leakage at the outer air seal shoes.

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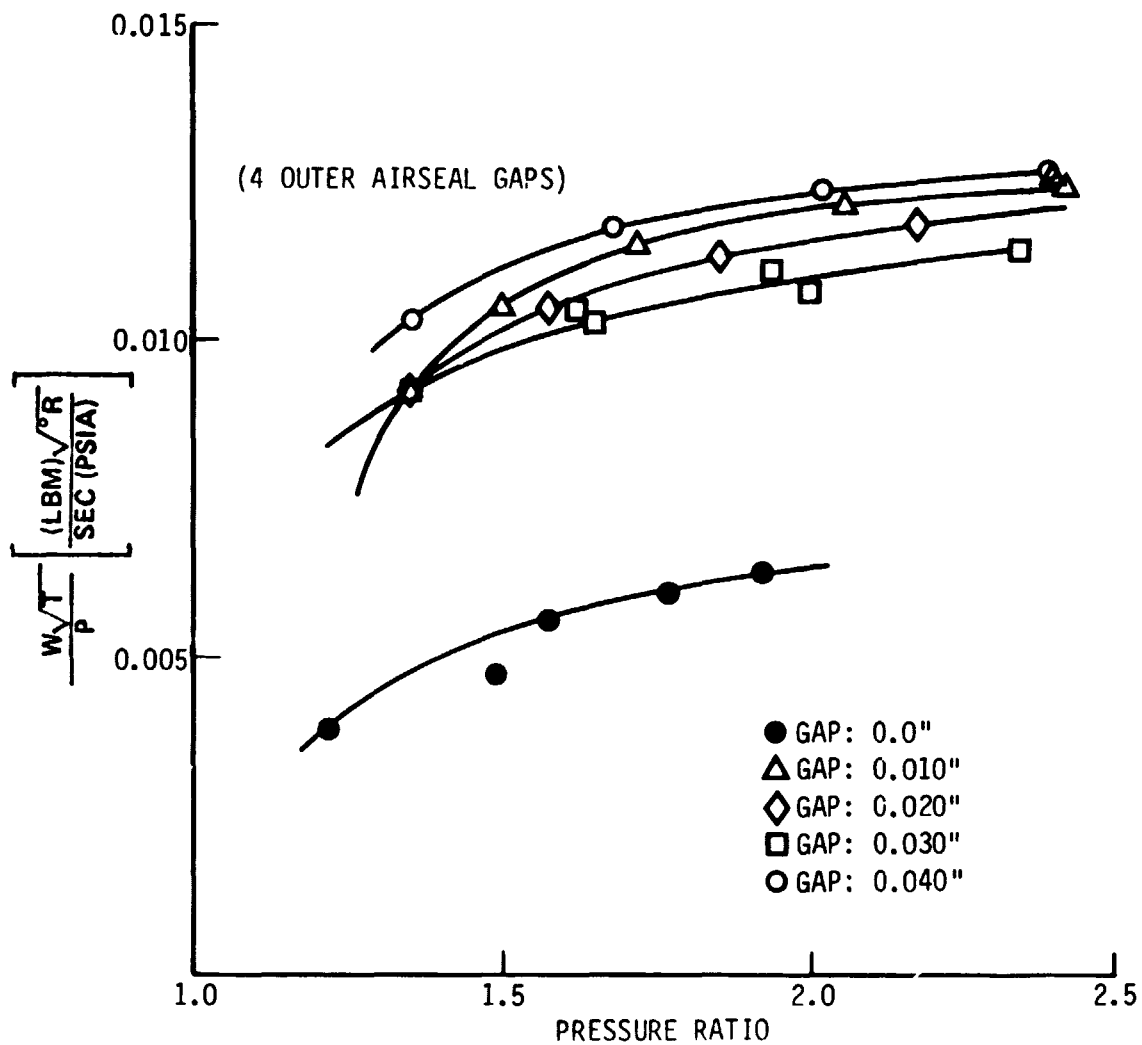


Figure 38 Leakage of the Outer Air Seals With Feather Seals - The effective areas of the feather seals were independent of gap size.

Having established the "raw" leakage, the feather seal was inserted and the data shown in Figure 38 was developed. Again, the "O-gap" case is an indication of the residual leakage in the rig. The interesting part about these data is that, with the seal in place, leakage through the gap was essentially insensitive to gap width once the gap was opened up. (The variations in flow parameter shown are most likely due to increasing end leaks as the gap width was increased). This insensitivity suggests that the feather seal "self-adjusts" in its slot with adjustments in gap size. The results are re-plotted on Figure 37 to show the effectiveness of the feather seal in reducing the total potential leakage flow.

6.3.2 Evaluation of "w" Seal Leakage

There was no provision in the rig to measure "w" seal leakage directly. As was done in the vane platform tests, the hope here was to be able to "plug" all of the leak paths except that which was to be evaluated. As it turned out, it was impossible to do this with any degree of certainty because of build-to-build variations. Consequently, the approach used was to measure a total leakage flow and then back-out flows due to feather seals and residuals; the result being a "reasonable estimate" of the leakage past the "W" seal. Results of this assessment are shown in Figure 39 in non-dimensional form.

The total leakage is represented by an average of the flow parameters with gaps open at a nominal "choked flow" pressure ratio of 2.0 shown in Figure 38. The feather seal contribution to this total was based on the assumption of a 2.3 mil/inch effective gap, typical of a tapered EDM feather seal slot with the feather seal in place.

As mentioned, it was impossible to isolate all of the residual leak paths in the rig. Consequently, an attempt was made to isolate "first-order" leaks. This isolation was done by plugging as many leak paths as possible in order to force as much of the flow as possible out through the feather seal and the "w" seal. The difference between this seal flow and the total flow was deemed as the "first-order" residual leaks and is shown in Figure 39. What remained, then, was leakage through the "w" seal and any "second-order" rig leakage that could not be isolated. The sum of these two was small and, in fact, was equivalent to an effective gap of one-quarter mil/inch. Obviously, "w" seal leakage would be somewhat less.

Summarizing these results:

Feather seals were successful in reducing leakage at the outer air seal shoes. Furthermore, leakage flow was essentially insensitive to gap width, once the gap was opened up. For example, with the feather seals in place, there was no significant leakage increase when the gap was increased from 0.010 in. to 0.040 in. In addition, the "w" seal was shown to effectively control leakage at the junction of the outer air seal and the active clearance control support rail.

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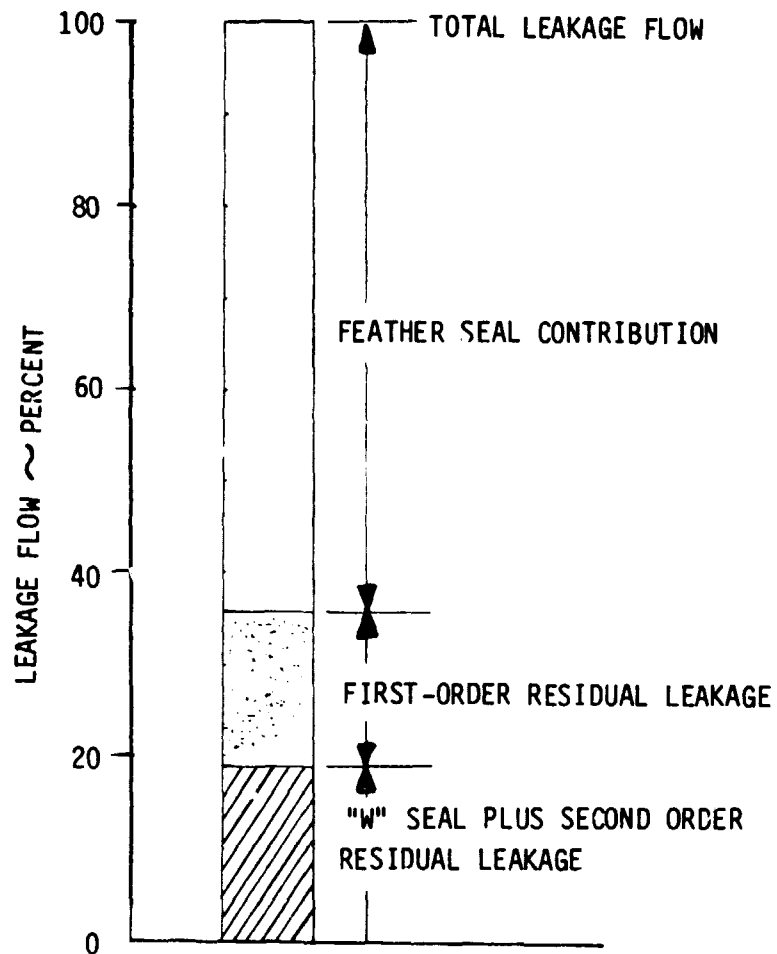


Figure 39 Contributions to Total Leakage Flow - "W" seal leakage is small compared to the total.

7.0 CONCLUSIONS

DISK-BLADE ATTACHMENT

- o Flow in the blade attachment rig were much lower than originally predicted.
- o Deflections of the sideplates in the blade attachment rig due to thermal and centrifugal loads may provide less than the anticipated required areas for coolant flows.
- o The "W-seal" at the outer radius of the sideplate had no effect on the leakage flow with all parts in perfect alignment. Significant leakage reduction will result only if the seal is required to conform to any tolerance related irregularities in blade dimensions or twisting of the blades in the firtree slots.
- o The full length blade damper design will reduce leakage; surface finish on the mating surfaces is critical.

VANE ATTACHMENT

- o In the vane rig, there were no significant differences in minimum leakage between ten and twenty mil feather seals, although for a given slot width, a ten mil feather seal permits greater relative "tilt" motion between platforms.
- o Slots formed by grinding leaked significantly less than those formed by EDM. This was for the feather seal proper and did not include end leaks. Therefore grinding would be the preferred method, particularly if the slots are straight and can be extended to the endwall. Both methods may require some development before they can meet production standards.
- o The most significant source of feather seal leakage is the areas opened at the ends or the intersection between two seals. These areas must be reduced.
- o Allowing seals to overlap--one extending past the other in a "T" intersection--opens a leak path. Therefore, overlap should be avoided if at all possible.
- o Modifying a two-piece feather seal configuration by putting either a crook in one seal to cover the intersection, or replacing the two seals with a single curved seal, had no significant impact on leakage.
- o A closely controlled seal length and a geometry which minimizes rotation are required to minimize end leaks and intersection leaks.

- o The preferred feather seal slot configuration for the vane platform is two pieces, with no overlap of the slots. Slots should be parallel-sided, and preferably ground to improve the surface finish.
- o With the preferred configuration, it is possible to achieve a feather seal effective gap equal to or less than one mil per inch.
- o Wire rope, in its present state of development, is not a feasible sealing concept for EEE turbine applications. However, the "hybrid" concept is promising and should be considered for further development.

BLADE OUTER AIRSEAL

- o Feather seals were successful in reducing leakage at the outer air seal shoes.
- o Leakage flow was essentially insensitive to platform gap width, once the gap was opened up. For example, with the feather seals in place, there was no significant leakage increase when the gap was increased from 0.010 in. to 0.040 in.
- o The "w" seal was shown to effectively control leakage at the junction of the outer air seal and the active clearance control support rail.